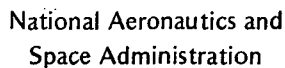


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John J. Dougherty, III
Lawrence D. Barrett

By
Boeing Vertol Company
Philadelphia, Pennsylvania

for



April 1978

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RESEARCH REQUIREMENTS
TO IMPROVE RELIABILITY
OF CIVIL HELICOPTERS

NASA CR-145335

Dougherty
Barrett

March 1978

NASA CR-145335

**RESEARCH REQUIREMENTS TO IMPROVE
RELIABILITY OF CIVIL HELICOPTERS**

By John J. Dougherty, III
and Lawrence D. Barrett

Prepared under Contract No. NAS1-13624 by
Boeing Vertol Company
Philadelphia, Pennsylvania

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ABSTRACT

This report documents the basic research and development required, as well as other changes possible within the state of the art, to achieve a substantial improvement in the reliability of civil helicopters.

Federal Aviation Agency civil helicopter Malfunction or Defect (M or D) reports were reviewed to identify and prioritize the problems, supplemented with military helicopter data only where deemed necessary.

The costs of unreliability in terms of unscheduled on-aircraft maintenance manhours and the costs of repair components and materials are included.

A listing of specific R&D recommendations is provided with an estimation of the pay-offs, timing, and development costs.

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This report was prepared by the Boeing Vertol Company for the National Aeronautics and Space Administration, Langley Research Center, under NASA Contract NAS1-13624. William Snyder was NASA Program Manager for these studies. The Boeing Project Manager was Kenneth T. Waters.

This study has shown that 78 percent of the reliability problems of civil helicopters can be categorized into 30 problems. These problems were analyzed to determine causal factors and to recommend corrective action. Of the 30 problems that were analyzed, the following table lists their relative impact by subsystem:

<u>Subsystem</u>	<u>Relative Failure Rate (%)</u>	<u>Unscheduled Maintenance Manhours (%)</u>	<u>Repair Parts Cost (%)</u>
Propulsion (Turbine power) †	35.3	25.1	66
Drive	13.9	35	21.3
Rotor	12.2	19.7	11.4
Airframe	19.9	10.1	1.2
Landing Gear (Floats)*	9.4	5.6	
Fuel	5	1.1	
Hydraulics	4.1	2.8	

†Only turbine-powered helicopters were included in this study.

*An aggressive reliability improvement program has virtually eliminated floats from the problem list subsequent to the data received for this study.

In terms of unscheduled maintenance manhours and cost of repair parts, the propulsion, drive, and rotor subsystems represent over 80 percent of the reliability problem. Since these subsystems also have a major impact on mission reliability (aborts) and safety, it is clear that major emphasis should continue to be placed on improving these subsystems. Because of the significant number of problems and the unscheduled maintenance manhours involved, air-frame reliability also needs improvement.

This study has defined research and development that should be conducted to substantially improve reliability of civil helicopters and thereby reduce operation and maintenance costs. The highest priority programs are listed below with estimated nonrecurring costs and timing in months:

	<u>Nonrecurring (\$ x 1,000)</u>	<u>Time (mo)</u>
Propulsion (turbine engines)		
● Fuel control and governor:		
Study failure modes and develop diagnostic fault-isolation techniques	400	36
● Compressor/turbine failures:		
Study failure modes and application of inlet separators	400	36

	<u>Nonrecurring</u> <u>(\$ x 1,000)</u>	<u>Time</u> <u>(mo)</u>
Drive		
● Transmission gear and bearing spalling: Materials development per reference 1	500	36
● Gear scuffing and spalling: Lubricant development	150	24
● Main and tail rotor gearbox housing cracks: Vibration reduction per reference 2	6,300	60
Rotor		
● Tension-torsion blade retention: Develop bearingless main rotor, reference 15	---	—
● Main and tail rotor control bearings: Continue development of elastomeric and dry-lube bearings	800	36
Airframe		
● Structural cracking and unbonding: Implement composite airframe structures program, reference 3, and implement vibration reduction program, reference 2	---	—

Many areas of unreliability can be improved by application of existing technology. Among the more prominent are:

1. Changeover to fiberglass composite rotor blades
2. Use of more effective turbine-engine inlet separators and screens to reduce FOD and compressor erosion
3. Introduction of an aggressive engine failure analysis and fix program
4. Improve durability of airframe fasteners and small hardware
5. Redesign and testing to reduce spalling of transmission bearings
6. Redesign to improve lubrication of drive shaft hanger bearings
7. Redesign main transmission housings on one model helicopter to reduce mounting lug cracking
8. Use the latest gear materials and improved process and quality controls to reduce tooth spalling and scuffing problems
9. Improve corrosion resistance of rotor components through better coatings that are damage-resistant
10. Apply the latest technology in hydraulic actuator seals to reduce seal leaking
11. Product improvement of fuel pressure switches and fuel pumps

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1.2 INTRODUCTION

The major reliability problems of the civil helicopter fleet as reported by helicopter operational and maintenance personnel are documented in this report. An assessment of each problem is made to determine if the reliability can be improved by application of present technology or whether additional research and development are required.

The reliability impact is measured in three ways:

- The relative frequency of each problem in the fleet.
- The relative on-aircraft manhours to repair, associated with each fleet problem.
- The relative cost of repair materials or replacement parts associated with each fleet problem.

The primary source of problem identification and prioritization is the FAA Malfunction or Defect report (M or D), FAA Form 8330. This report may be filed by pilots, operators, and maintenance or repair personnel and is mandatory for the certified domestic repair facility. The data reporting is not mandatory for all personnel and all types of malfunctions, particularly for those malfunctions not immediately critical to flight safety. This FAA M or D report is, however, the most complete source of reliability data with inputs from all segments of the civil helicopter fleet that is known to the authors. Thus it is best suited as a data source for any quantitative evaluation of the helicopter reliability problem.

This data was supplemented in a few cases by military data, when the same helicopter or subsystem was used in both civil and military applications. All data from sources other than the FAA M or D report is referenced in the text.

The data reviewed covered the period of 1971 through 1976 and covered only turbine-engine aircraft. This was done because virtually all reported data for the reciprocating-engine-powered helicopters was for the Bell Model 47, a model last manufactured in 1973 and considered atypical of the present-day product.

The flight hour base of the turbine-engine-powered civil helicopter fleet during this 6-year period was approximately three million hours. The annual total civil helicopter fleet flight hours in Figure 1 are shown for the past nine years with yearly usage projected to 1985. The turbine-powered helicopter annual usage has been steadily increasing, exceeding that of the piston-engine-powered aircraft several years ago. The proportion of the total fleet hours taken by the turbine-engine-powered machines is expected to continue to rise as the civil helicopter fleet is modernized.

A typical distribution of flight hours among the various helicopter models is shown in Table 1, which gives the 1975 turbine-powered helicopter fleet records. The Bell Model 206

dominates this civil fleet and the civil helicopter reliability records reflect the high usage of this helicopter.

Typical missions for the civil helicopter fleet are given in Figure 2, which gives the percentage of flying hours expended in 1974-75 for each type of flying.

TABLE 1. 1975 U.S. GENERAL AVIATION FLIGHT HOUR DISTRIBUTION FOR TURBINE-POWERED HELICOPTERS

Manufacturer Model	Percentage of Turbine-Powered Flight Hours
Single Engine	
Bell 206	56.9
Bell 205	5.6
FH 1100	4.4
Hughes 369	11.1
Alouette III	6.5
Sud Aviation SA341G	
Aerospatiale SA315B	
SNIAS SA318C	
Twin Turbine	
Bell 212	15.5
Sikorsky S-61, S-64, S-58T	
Boeing Vertol 107, BO-105	
Total Turbine-Powered Flight Hours	820,549
Data from reference 4	

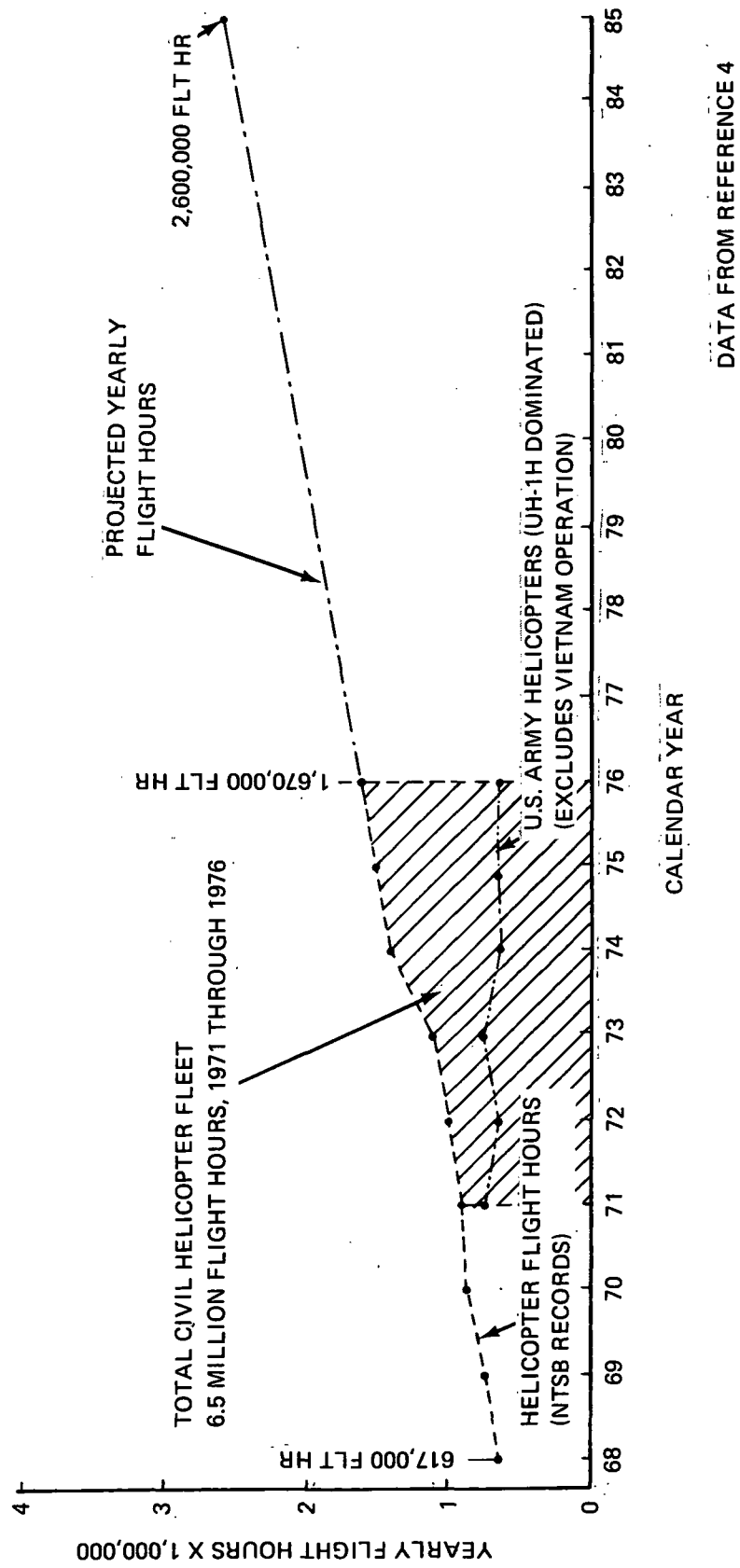


Figure 1. Current and predicted flight hours of U.S. general aviation helicopters

DATA FROM REFERENCE 4

TYPE OF FLYING

AIR TAXI (CHARTER, OFFSHORE DRILLING
— PERSONNEL AND EQUIPMENT)

INDUSTRIAL (CONSTRUCTION
— PROFESSIONAL PILOTS)

CORP/EXEC (PROFESSIONAL PILOTS)

AGRICULTURAL (SEEDING, SPRAYING)

OTHER (POLICE, FIRE, SAR, MISC)

INSTRUCTION, TRAINING

BUSINESS (NONPROFESSIONAL PILOTS)

PERSONAL (PLEASURE)

DATA BASE: 1974 AND 1975
2,960,070 FLYING HOURS

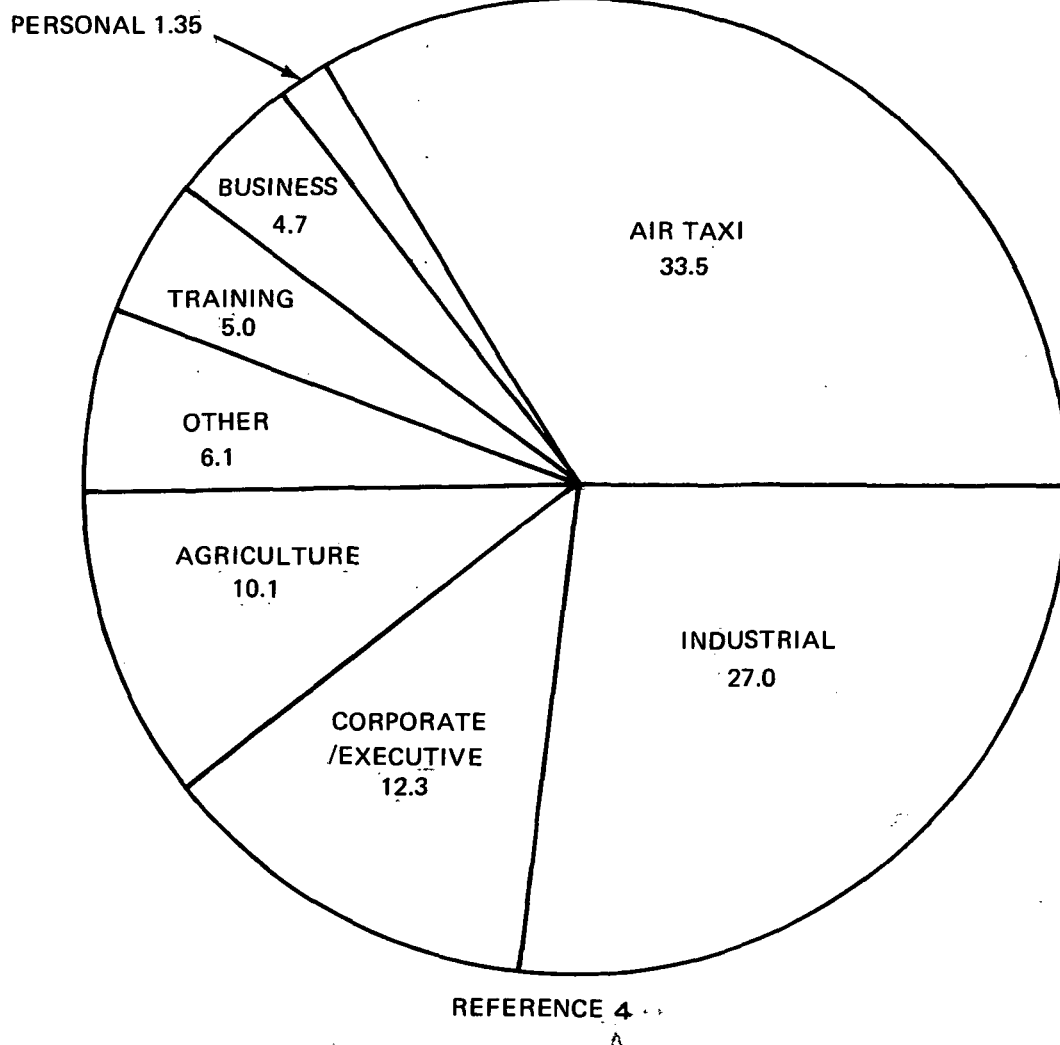


Figure 2. Percentages of civil helicopter flying hours by kind of flying

1.20 DEFINITION OF THE IMPACT OF RELIABILITY

What is reliability? Webster's dictionary gives the definition, "suitable or fit to be relied upon, worthy of dependence or reliance giving the same results on successive trials" (ref. 5).

Reliability to the military is "the probability that an item will perform its intended function for a specified interval under stated conditions" (ref. 6). Demonstration of reliability is usually expressed in terms of mean time between failure (MTBF), or failure rate, $\frac{1}{\text{MTBF}}$.

Each civil helicopter operator probably has his own priorities as to what factors are most important in demonstrating improved reliability. There may be agreement among operators that the highest priority of corrective action should be directed at preventing malfunctions that result in mission aborts. These are the reliability problems that most affect the helicopter task completion and also have flight safety implications. Fortunately these are a small part of the helicopter reliability problem; one summary of reliability data for the OH-58 aircraft (the military version of the Bell Model 206) showed that less than 0.4 percent of malfunctions requiring repair or replace maintenance actions resulted in mission aborts (ref. 7).

The mean time between failure (MTBF) of a helicopter is certainly an important reliability parameter. The adverse effect of a low MTBF is increased if the malfunction has the following characteristics:

- has safety of flight implications
- prevents mission completion
- causes extensive downtime of the helicopter
- requires many maintenance manhours to correct
- requires expensive repair parts
- requires not-normally-inventoried replacement parts.

A civil helicopter operator may be very tolerant of a helicopter with a high malfunction rate (and a resulting low MTBF) if he has no mission-affecting failures, the helicopter availability is high, and the frequent maintenance actions are very inexpensive to correct in terms of manhours and materials. Some light bulb and rivet/screw failures are examples of this type of malfunction. Conversely, a high-reliability helicopter in terms of a high MTBF may be considered unacceptable if the relatively few malfunctions are of a nature that adversely affect availability or flight safety and result in a high repair cost per flight hour. Engine failures fall in this category.

In this report the three parameters chosen as indexes for determining the impact of reliability are the failure frequency, on-aircraft manhours to repair, and the cost of repair parts. The rationale for the selection of these indexes is as follows:

- Submission of the FAA M or D report is not obligatory for many helicopter personnel; the defects that are reported tend to be those considered most relevant by the operational or maintenance personnel, primarily serious defects and those endangering the safe operation of the aircraft. Thus the reported failure frequency obtained from this data source is weighted toward the more significant failures.
- The FAA M or D reports contain no information identifying malfunctions resulting in mission aborts, nor do they give information from which the impact of the malfunction on helicopter availability can be determined. Therefore this parameter could not be evaluated from the reliability data. The subject is discussed separately, however.
- The on-aircraft manhours to repair and the cost of repair materials and components can be determined from the malfunction descriptions and relative failure frequencies obtained from the FAA M or D data, either by maintenance engineering analysis procedures or, on some models of helicopter, from the extensive data records of equivalent military models. These are important parameters in the determination of an operator's manpower requirements and operating expense.
- Helicopter downtime and the normal inventory of spare parts are not parameters determinable from the FAA M or D reports and are somewhat dependent on the size of each individual operator's fleet and maintenance shop, as well as his operating practices, and so were not possible to evaluate in this study.

3.0 THE RELIABILITY PROBLEM

3.1 Problem Identification

Over 1,500 Federal Aviation Agency Malfunction or Defect reports (FAA M or D) covering the turbine-engine-powered civil helicopter fleet for the years 1971 through 1976 were reviewed to determine the subsystems and components responsible for the civil helicopter reliability problem. The distribution of reported malfunctions by subsystem is given in Figure 3.

The frequency of malfunction of each component was taken as a standard for problem identification. Major problems were determined in three ways:

- Problems with the highest reported frequency of occurrence.
- Problems requiring the highest on-aircraft unscheduled manhours to repair or replace associated components. The reliability impact was determined by the magnitude of the product of the manhours per problem occurrence and the frequency of problem occurrence.
- Problems with the highest costs of repair materials and replacement components. The reliability impact was determined by the product of cost per problem occurrence and the frequency of problem occurrence.

The 20 most frequently reported problems were identified for further analysis; Figure 4 shows the relative failure rate of each of these problems.

These 20 problems were reported in over 70 percent of the FAA M or D reports and thus any alleviation of these problems would have a large impact on improving reliability.

A second review was made to find the problems that required the largest expenditure of unscheduled on-aircraft maintenance manhours. Figure 5 shows the relative impact of the top 20 reliability problems where the product of unscheduled maintenance manhours per problem occurrence and the frequency of problem occurrence is used as a standard for evaluation. Seven of these problems were not previously identified on the 20 most frequently reported list.

A third review of problems was made to determine those problems having the greatest impact on reliability when the cost of repair materials and replacement components was considered. Figure 6 shows the relative impact of the top reliability problems when the product of the cost of repair materials and replacement components per problem occurrence and the frequency of problem occurrence is used as a standard for evaluation. As might be expected, several problems with a relatively low failure rate had a large impact on reliability repair cost and vice versa. Again, several new problems were identified for a major reliability problem list.

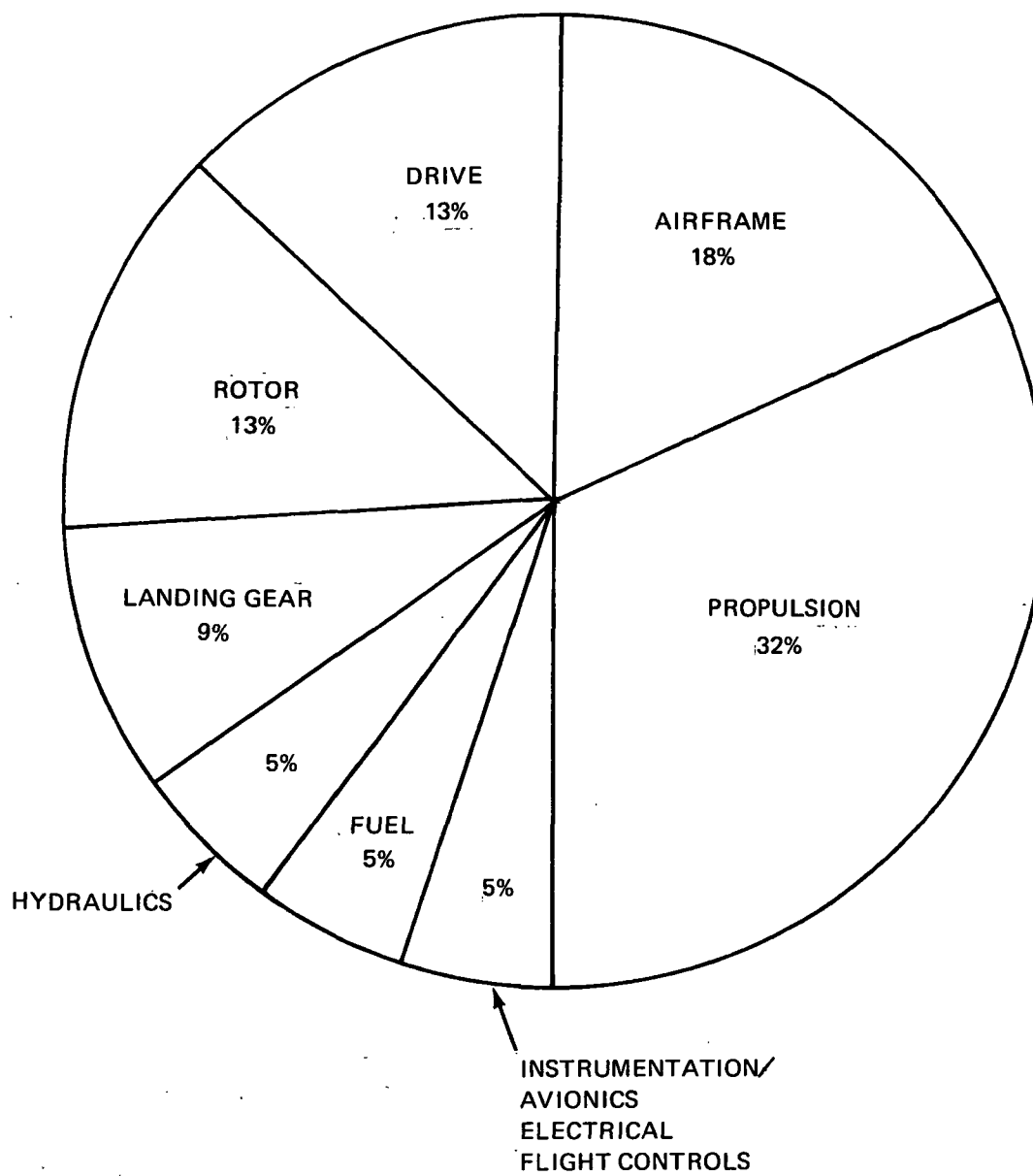


Figure 3. Distribution of reported reliability problems by helicopter subsystem

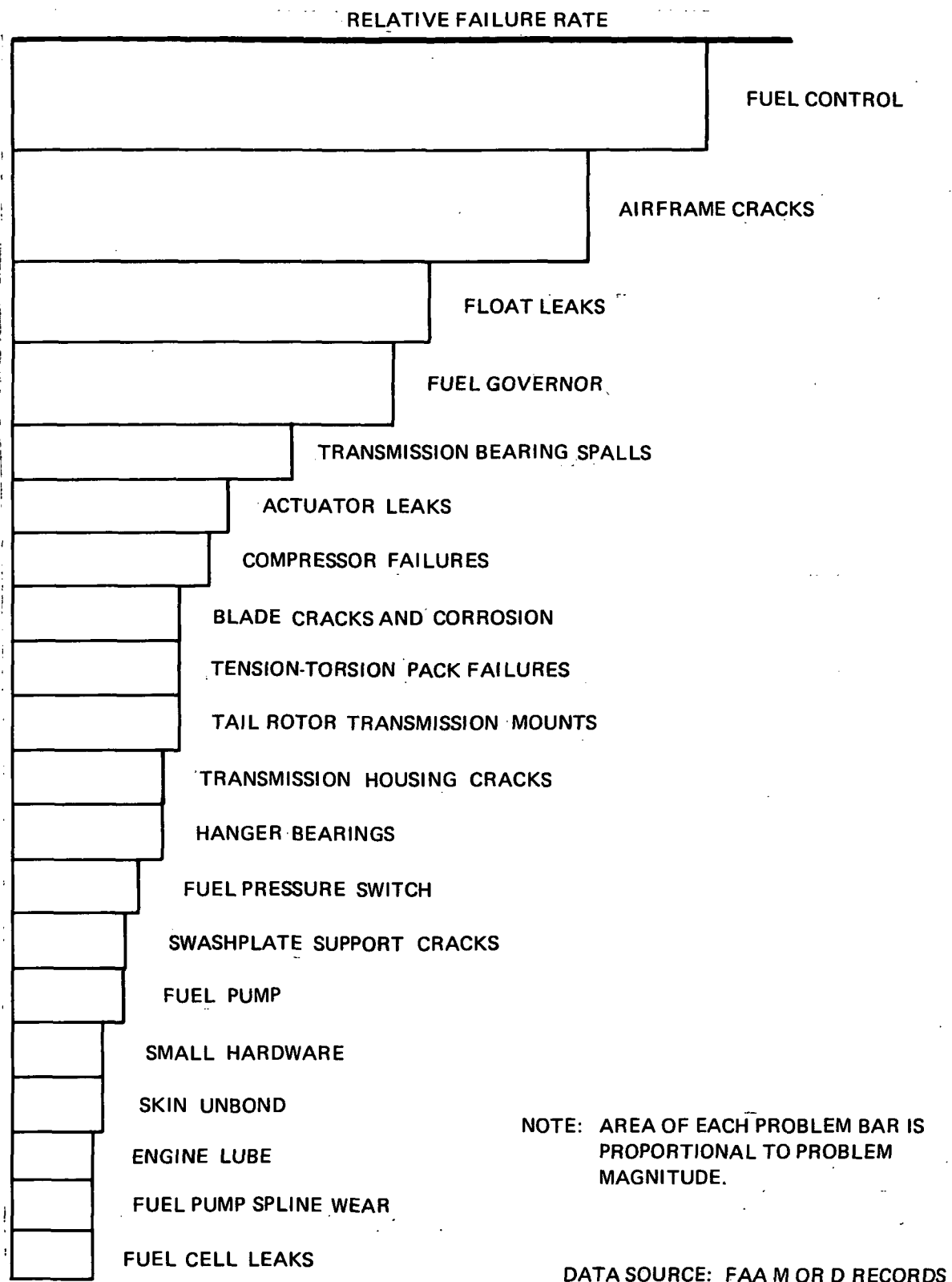
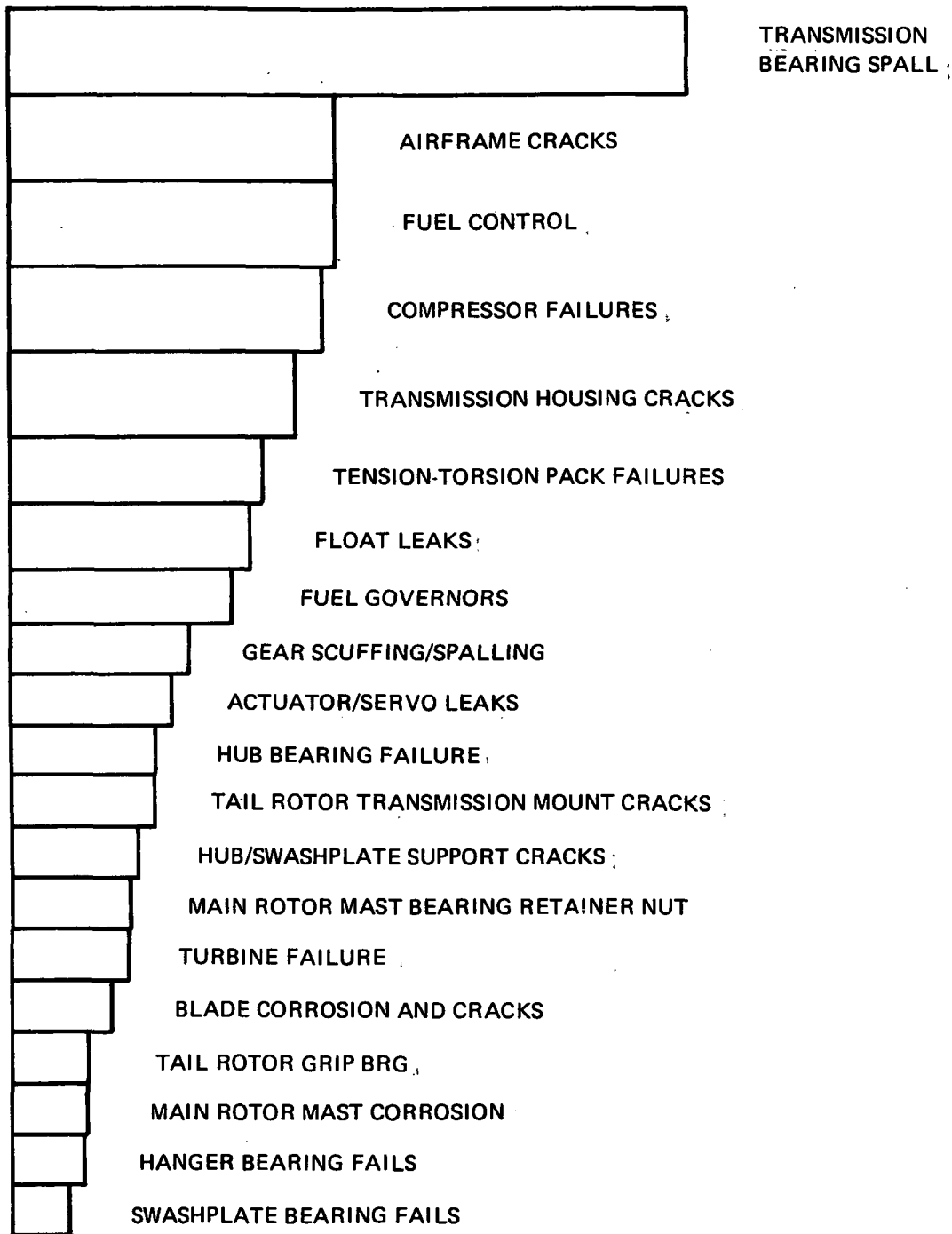


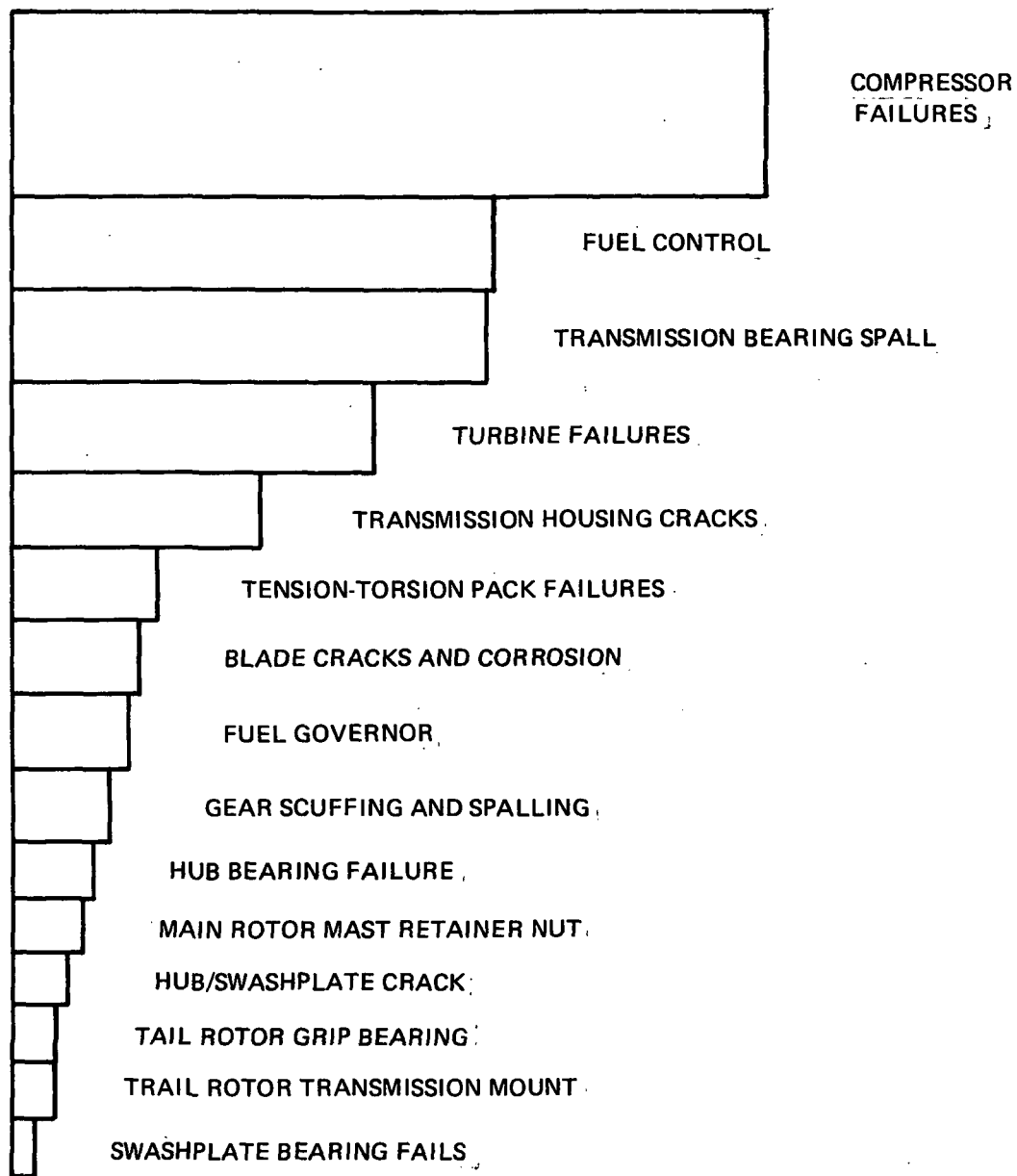
Figure 4. Top 20 most frequently reported reliability problems of civil helicopters

RELATIVE MANHOUR REQUIREMENT



NOTE: AREA OF EACH PROBLEM BAR IS PROPORTIONAL TO PROBLEM MAGNITUDE.

Figure 5. Top 20 maintenance manhour problems of civil helicopters



NOTE: AREA OF EACH PROBLEM BAR IS PROPORTIONAL TO PROBLEM MAGNITUDE.

Figure 6. Top 15 relative repair parts cost problems of civil helicopters

Thirty reliability problems were selected for further analysis by combining the lists of high frequency of occurrence, high maintenance manhours, and high materials/components cost problems. This combined list accounted for more than three-quarters of the reported malfunctions, as shown in Figure 7.

A breakdown of these 30 problems by subsystem is given in Table 2, which shows the problems arranged within each subsystem in order of decreasing frequency of occurrence, decreasing unscheduled manhour requirements, and decreasing repair parts cost.

No one problem in the instrumentation, avionics, electrical, or flight controls had sufficient reported failures to be represented on this major problem list.

Figure 8 shows the reliability impact by subsystem of these 30 major problems based on frequency of reported problem occurrence. Figure 9 shows the subsystem reliability impact based on the unscheduled maintenance manhours associated with these problems. Figure 10 shows the subsystem reliability impact based on the relative cost of repair materials and replacement components associated with these problems.

In reviewing Figures 8, 9, and 10, the following conclusions can be drawn:

- The propulsion subsystem has the largest reliability impact of any subsystem when measured by either the frequency of reported problem occurrence or the cost of repair parts standards and has the second highest impact in terms of the on-aircraft unscheduled maintenance manhour requirement. This subsystem accounts for more than a third of the reported malfunction occurrences, a quarter of the unscheduled maintenance manhours, and two-thirds of the costs of repair materials and parts.
- The airframe subsystem, which had approximately one-fifth of the reported malfunctions, can be seen to have an almost negligible impact on the cost of repair materials and parts. However, the reported malfunctions of this subsystem cause 10 percent of the unscheduled maintenance manhours associated with the 30 major problems.
- The drive subsystem has the largest impact on unscheduled maintenance manhours of any subsystem. The identified drive subsystem problems result in more than a third of the unscheduled maintenance manhours associated with the major problems. The drive is the second highest subsystem in terms of the relative cost of repair parts, resulting in over a fifth of the parts cost attributed to these major problems.
- The drive and rotor subsystems are nearly equal in reported failure rates, but the rotor system has approximately half the reliability impact of the drive in terms of unscheduled maintenance manhours and associated cost of repair parts.
- The three subsystems, propulsion, drive, and rotor, constitute 98 percent of the reliability repair cost.

ALL REPORTED CIVIL HELICOPTER MALFUNCTIONS OR DEFECTS, 1971 THROUGH 1976

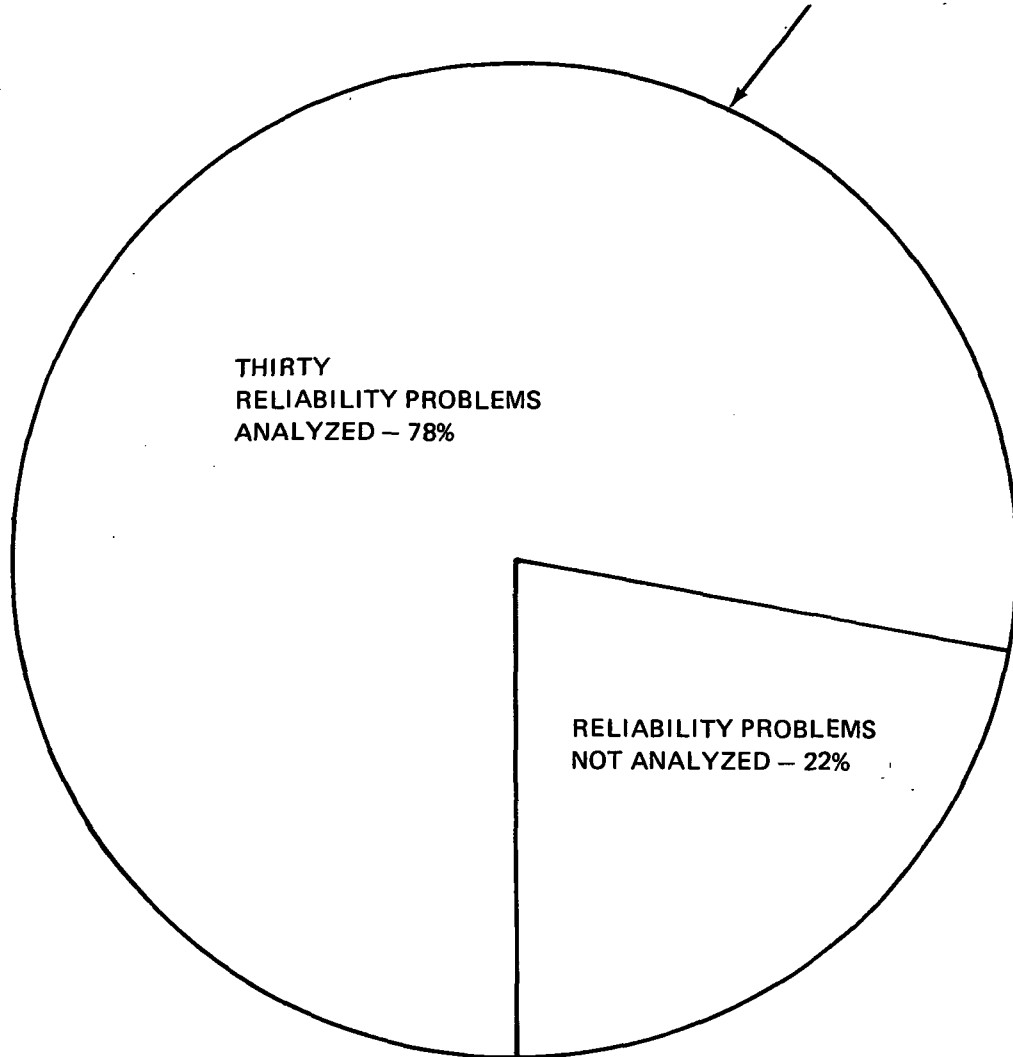


Figure 7. Thirty analyzed reliability problems represent more than three-quarters of the malfunctions or defects reported to the FAA

TABLE 2. COMBINED RELIABILITY PROBLEM SUMMARY

Subsystem	Frequency (In order of decreasing reliability impact within each subsystem)	Unscheduled Maintenance Manhours (In order of decreasing reliability impact within each subsystem)	Cost of Repair Materials/Components (In order of decreasing reliability impact within each subsystem)
Propulsion	Fuel control malfunction Fuel governor malfunction Compressor failure Engine lubrication Fuel pump spline wear Turbine failure	Fuel control malfunction Compressor failure Fuel governor malfunction Turbine failure Fuel pump spline wear Engine lubrication	Compressor failures Fuel control malfunction Turbine failure Fuel governor malfunctions Fuel pump spline wear Engine lubrication
Airframe	Airframe skin and structure cracks Small hardware failure or loss Skin unbonding	Airframe skin and structure cracks Skin unbonding Small hardware failure or loss	Airframe skin and structure cracks Skin unbonding Small hardware failure or loss
Drive	Transmission bearing spalling Tail rotor transmission mount cracking Transmission housing cracks Hanger bearing failure Gear scuffing and spalling Drive shaft spline wear	Transmission bearing spalling Transmission housing cracks Gear scuffing and spalling Tail rotor transmission mount Hanger bearing failure Drive shaft spline wear	Transmission bearing spalling Transmission housing cracks Gear scuffing and spalling Tail rotor transmission mount Drive shaft spline wear Hanger bearing failure
Rotor	Blade cracks and corrosion Tension-torsion assembly failure Swashplate support cracking Rotor hub bearing failure Main rotor retention nut failure Tail-rotor grip bearing failure Swashplate bearing failures Main rotor mast corrosion Rotor hub leaking Rotor hub corrosion	Tension-torsion assembly failure Rotor hub bearing failure Swashplate support cracking Main rotor retention nut failure Blade cracks and corrosion Tail rotor grip bearing failure Main rotor mast corrosion Swashplate bearing failure Rotor hub leaking Rotor hub corrosion	Tension-torsion assembly failure Blade cracks and corrosion Rotor hub bearing failure Main rotor retention nut failure Swashplate support cracking Tail rotor grip bearing failure Swashplate bearing failure Rotor hub leaking Rotor hub corrosion Main rotor mast corrosion

TABLE 2 - Continued

Subsystem	Frequency (In order of decreasing reliability impact within each subsystem)	Unscheduled Maintenance Manhours (In order of decreasing reliability impact within each subsystem)	Cost of Repair Materials/Components (In order of decreasing reliability impact within each subsystem)
Landing Gear	Float leaking	Float leaking	Float leaking
Hydraulics	Flight control actuator leakage	Flight control actuator leakage	Flight control actuator leakage
Fuel	Fuel pressure switch failure Fuel pump failure Fuel cell leakage	Fuel pressure switch failure Fuel pump failure Fuel cell leakage	Fuel cell leakage Fuel pump failure Fuel pressure switch failure

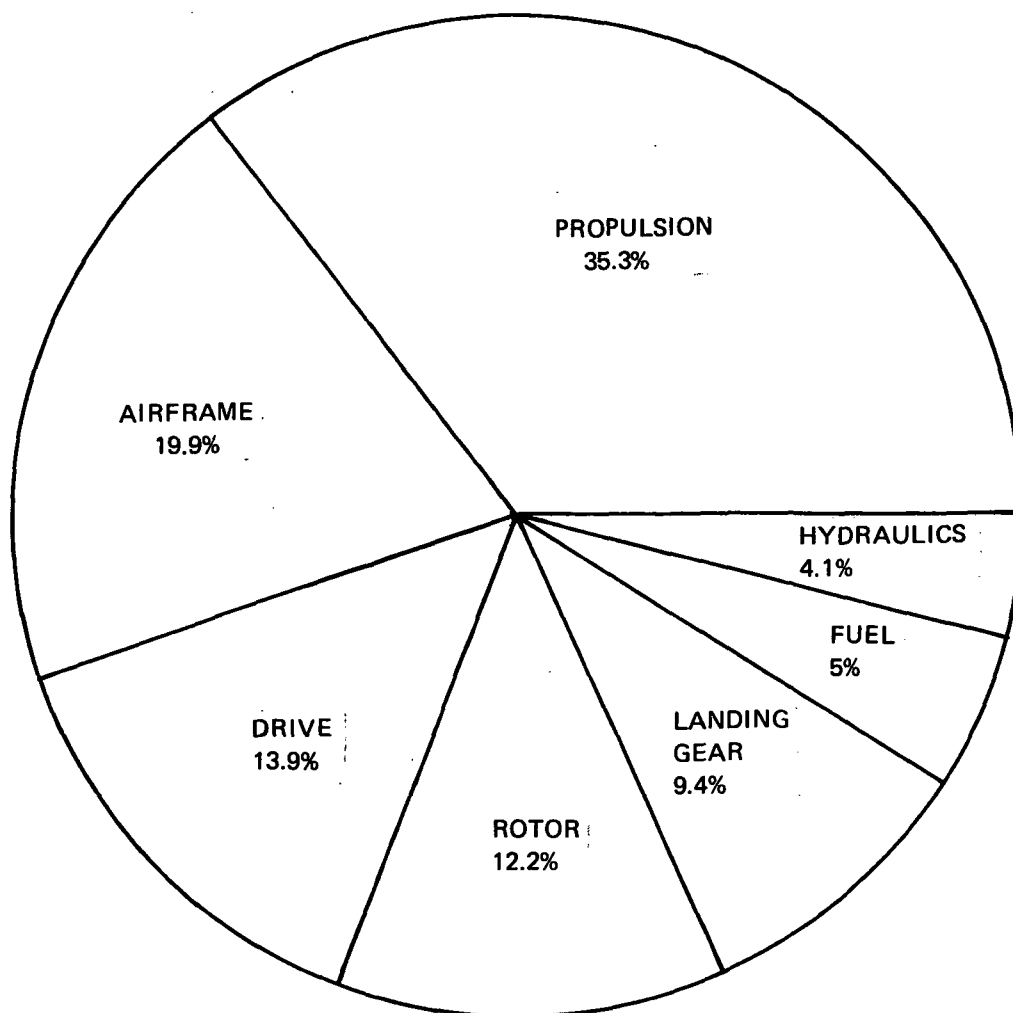
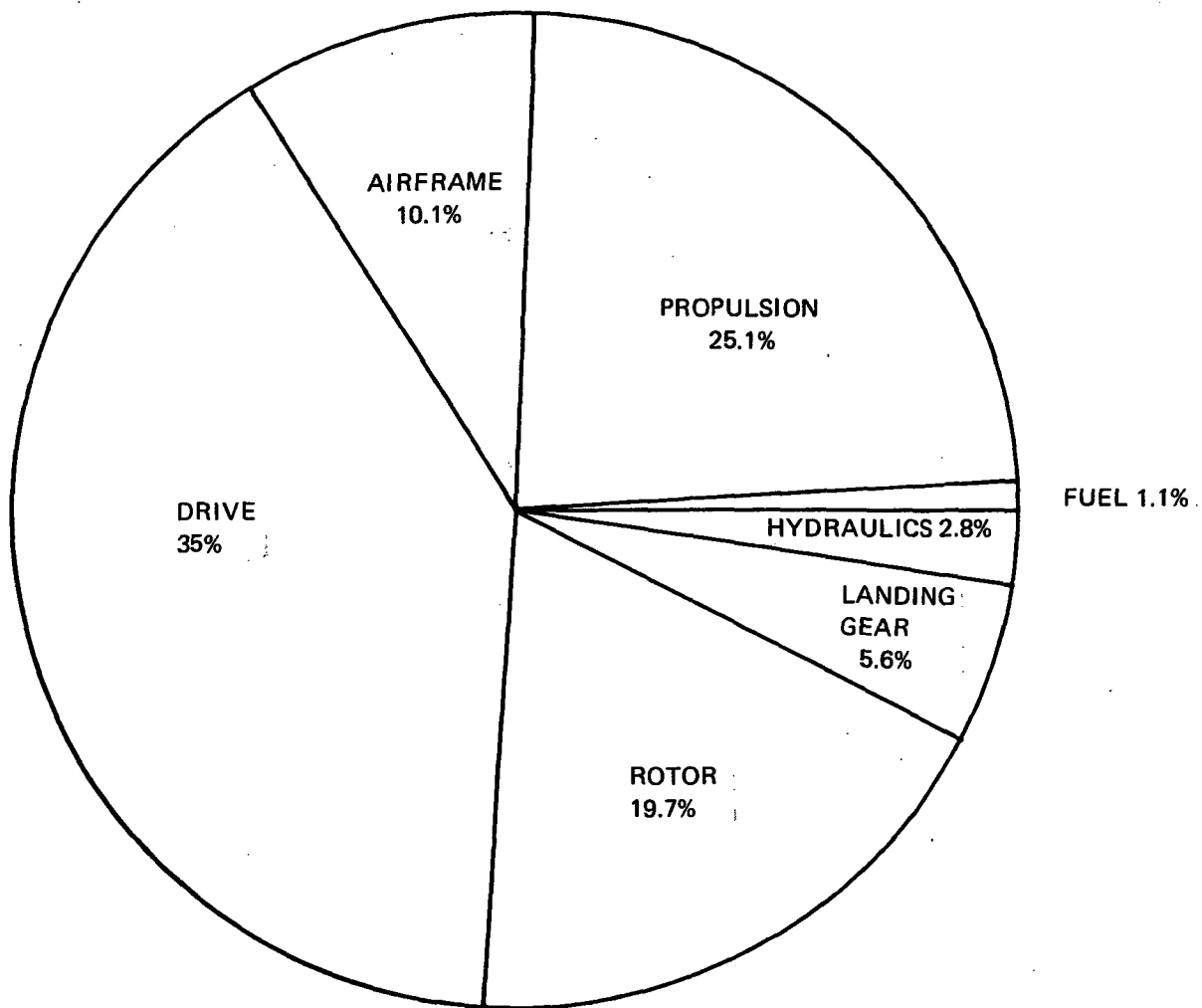
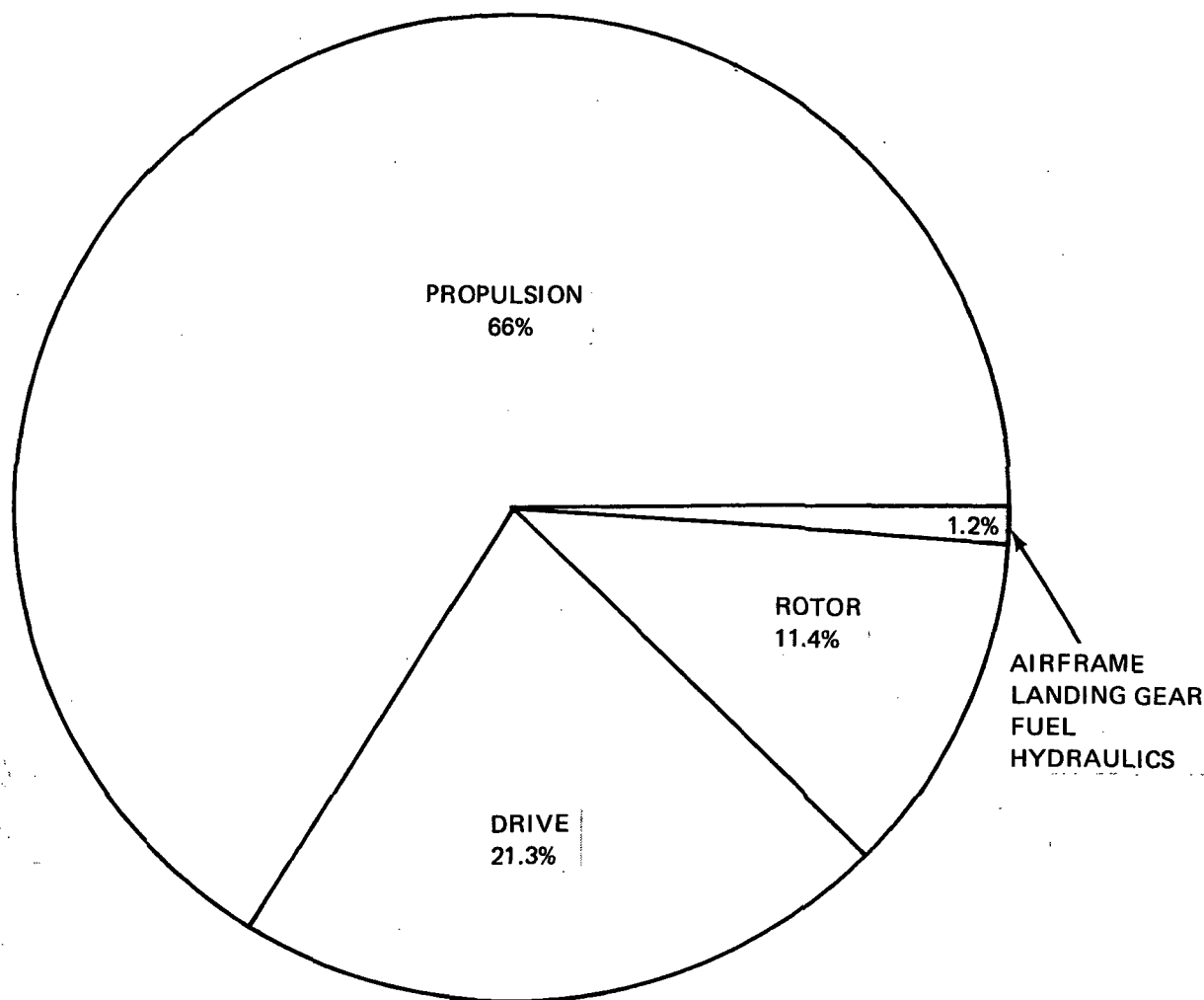


Figure 8. Major reliability problems of civil helicopters by relative failure rate of subsystems



NOTE: MANHOURS BASED ON ON-AIRCRAFT REMOVAL, REPLACEMENT, OR REPAIR ASSOCIATED WITH MAJOR PROBLEMS

Figure 9. Major reliability problems of civil helicopters by relative unscheduled maintenance manhours on subsystems



NOTE: COSTS BASED ON REPLACEMENT COMPONENTS
AND REPAIR MATERIALS

Figure 10. Major reliability problems of civil helicopters by relative costs of repair parts for subsystems

- The aggregate problems of the landing gear, hydraulic, and fuel subsystems which constitute nearly a fifth of the reported failures are nearly insignificant in terms of the reliability repair cost problem and are responsible for only a tenth of the associated major problem unscheduled maintenance manhours.

The subsystem reliability impact of these major problems is discussed in greater detail in the following section.

3.2 Subsystem Problem Discussion

This section gives a general discussion of the problems of each subsystem. A more detailed discussion of each problem on which this discussion is based is contained in the appendix.

3.2.1 Propulsion Subsystem. — The propulsion subsystem is the primary reliability problem of the turbine-engine-powered civil helicopter operator.

As has been shown in Figures 8, 9, and 10, the propulsion subsystem has the largest reliability impact of any subsystem in terms of the frequency of reported malfunctions and the associated cost of repair materials and replacement components and has the second largest impact on unscheduled on-aircraft maintenance manhours.

The major problems identified for this subsystem and the corresponding detailed technical analysis reference number in the appendix are:

- | | |
|--|------------|
| ● Fuel control problems | Problem P1 |
| ● Fuel governor problem | Problem P2 |
| ● Compressor failure | Problem P3 |
| ● Engine and accessory lubrication system failures | Problem P4 |
| ● Fuel pump spline wear | Problem P5 |
| ● Turbine failure | Problem P6 |

Figure 11 shows the contribution of each propulsion subsystem major problem to the entire subsystem reliability problem for each of the three reliability parameters of this study (relative frequency of occurrence, unscheduled maintenance manhours, and repair parts cost). In addition, the propulsion subsystem impact on the major problems of the entire civil helicopter for each reliability parameter is given for reference.

Malfunctions of the fuel control and the fuel governor can be seen to be the two most frequently reported problems. Fuel control problems require the largest percentage of unscheduled maintenance manhours, closely followed by compressor failures. Costs of repair components for compressor failures are the dominant factor in the parts costs of the propulsion subsystem, but repair costs associated with the fuel control, turbine failure, and fuel governors are also significant as the propulsion subsystem costs of repairs are two-thirds that generated by all civil helicopter major problems.

The major propulsion system problems are solved by a remove-and-replace operation. The appropriate accessory or the basic engine is then returned to the manufacturer or overhaul facility, since very few civil helicopter operators will do this type of specialized repair work.

Fuel controls and fuel governors are frequently removed and replaced as part of a diagnostic technique. Often the unit is subsequently found to be fully functional when examined by the overhaul facility. This may be an expensive means of troubleshooting as the costs of disassembly and examination of a functional unit can be very nearly as costly as examining a defective unit; however, this may be the most practical means of troubleshooting available to the small helicopter operator.

The costs incurred by a compressor or turbine failure are those of the return of the engine to the manufacturer and the necessity for a major overhaul. The cost per malfunction of this category of problem is clearly very high.

Engine and accessory lubrication system malfunctions and fuel pump spline wear problems are each responsible for approximately 5 percent of the propulsion subsystem major problem failure rate but aggregate less than 1 percent of system repair cost. This results from the ease of diagnosis and correction of these problems relative to the balance of the propulsion system.

The causes of the propulsion subsystem problems are very poorly defined. As the civil helicopter reliability problem is, to a large degree, a reflection of the propulsion subsystem problems, it is important to determine the causes of malfunctions.

A rather comprehensive study of military aircraft turbine engine R and M problems (ref. 8) gives some insight as to probable causes of malfunction of the civil helicopter propulsion subsystem, as follows:

- Fuel controls. Observed failure modes were:
 - Contamination from the actuating media or from the fuel itself causing sticking and binding of spools, leakage of valves, and clogged orifices.
 - Wear on moving or contacting elements.
 - Fatigue failures of springs, bellows, and retention devices.
 - Misadjustment, erroneous troubleshooting, etc.
- Compressors. FOD to the compressor vanes and blades was responsible for 27 percent of unscheduled engine removals.
- Turbine problems are principally with the nozzles as the result of thermal stresses, thermal weakening, and hot gas erosion.

A detailed study of civil helicopter turbine engine failure causes is in order in view of the magnitude of the propulsion subsystem reliability problem. For example, the civil

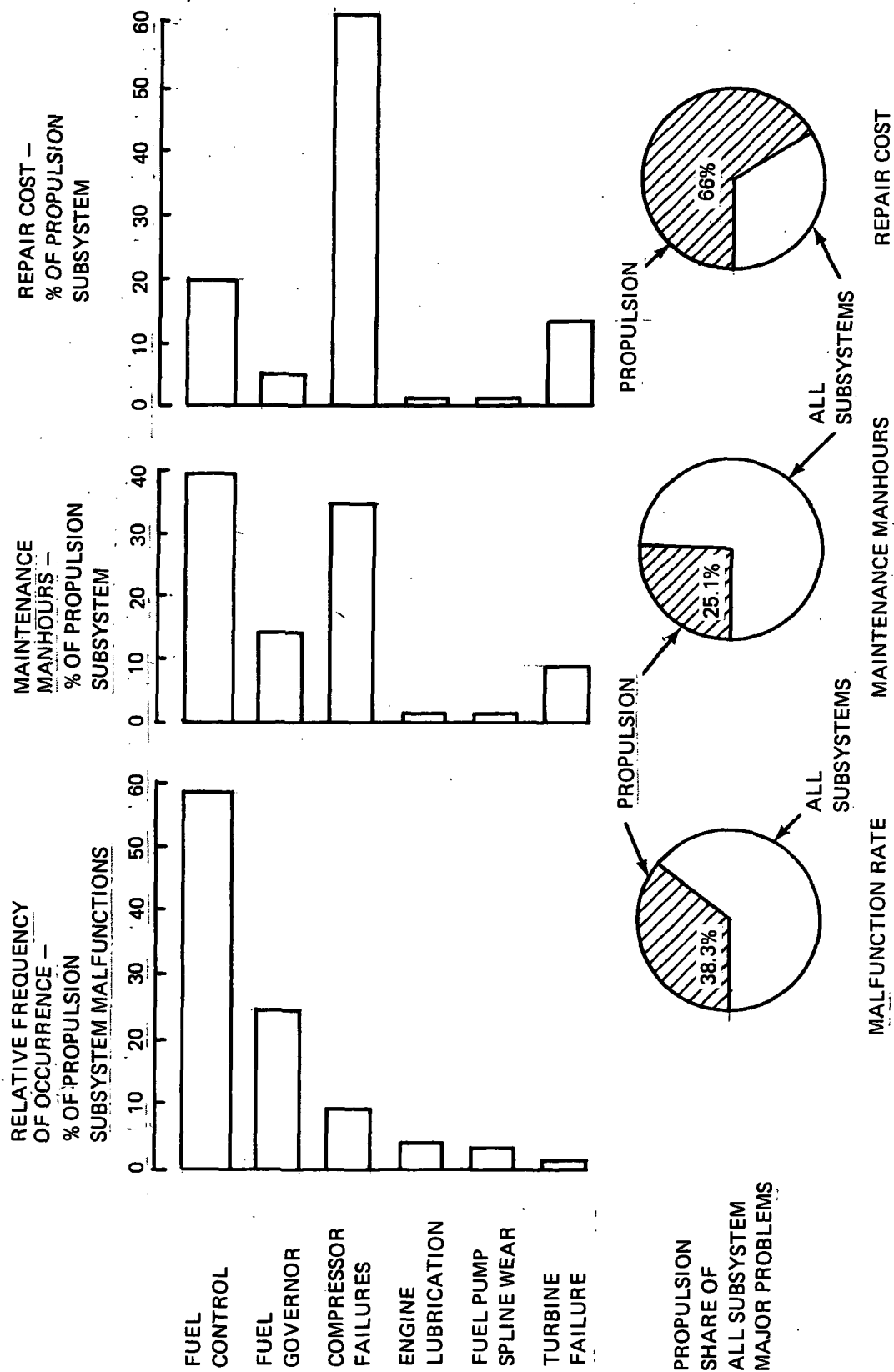


Figure 11. Distribution of propulsion subsystem reliability problems

helicopter FAA M or D data provides very little evidence of an FOD-related compressor failure problem. This may be a true situation, or it may be due to the operator's inability to determine FOD damage in the field. The review of military helicopter unscheduled engine removal causes of reference 8 indicates that the magnitude of the compressor problem on military helicopters is comparable to that of civil helicopters only if the FOD-related compressor problems are included in the comparison. As such, it is inferred that the civil operator may encounter FOD problems of a magnitude comparable to military users, although this issue does deserve additional research.

With regard to accessory/lube failures, again a comment on the civil helicopter data is required. Most of the failures included in this category are reported as lube system metallic contamination probably related to oil-lubricated bearing failures, although it is impossible to determine this without shop/overhaul data.

It is evident that the propulsion subsystem problem will not be alleviated unless the correct malfunction causes are known.

3.2.2 Airframe Subsystem. — The airframe subsystem ranks next to the powerplant subsystem as a reliability problem from the standpoint of reported malfunctions, as was shown in Figure 3.

Figures 8, 9, and 10 showed that, although the airframe subsystem accounts for nearly 20 percent of the reported major problem malfunctions, the associated airframe unscheduled on-aircraft maintenance manhours account for only 10 percent of the major problem man-hour rate and the associated airframe cost of repair materials or components for these problems is negligible.

The major problems identified for this subsystem and the corresponding detail technical analysis reference number of the appendix are:

- | | |
|--|------------|
| ● Airframe skin and structure cracking | Problem A1 |
| ● Small hardware loss or failure | Problem A2 |
| ● Skin unbonding | Problem A3 |

Figure 12 shows the contribution of each of the three airframe subsystem major problems to the entire subsystem reliability problem for each of the three reliability parameters of this study (relative frequency of occurrence, unscheduled maintenance manhours, and cost of repair parts). In addition, the airframe subsystem impact on the major problems of the entire civil helicopter is given for each reliability parameter for reference.

The dominating reported problem of the airframe subsystem, as shown in Figure 12, is skin and structure cracking. This problem accounts for more than 80 percent of the airframe reliability problems, whether measured against the frequency of problem occurrence, unscheduled maintenance manhours, or cost of repair parameters.

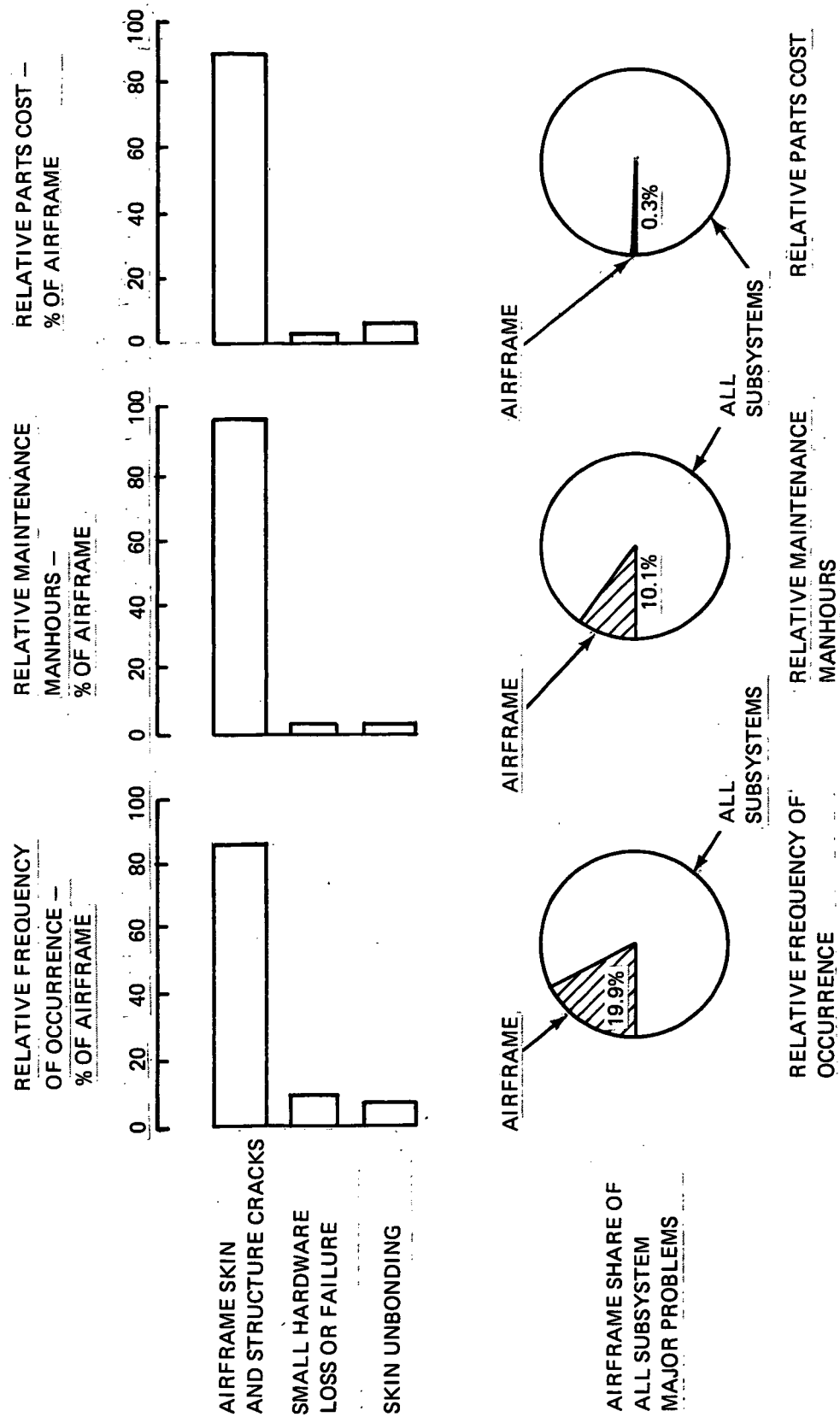


Figure 12. Distribution of airframe subsystem reliability problems

(10)

Skin and structure cracking has three principle causes:

- High localized vibration
- Load concentration at attachments of skin and structure
- Maintenance-oriented damage which results in a load concentration.

Small hardware and honeycomb panel skin unbonding problems also have maintenance-oriented damage as a prime causal factor. Rough handling of the small hardware — hinges, latches, and attaching rivets or screws — will fail or deform parts while the skin of metal honeycomb panels is very vulnerable to puncture loads. Helicopter vibration is a significant part of the small hardware problem, as well as improper design or manufacturing consideration for the tolerance variations of a fastener installation. Metal honeycomb panels have had a history of unbonding problems which have been traced to improper processing procedures, as well as internal corrosive attack caused by improper selection of bonding materials or improperly sealed panels.

Surprisingly, the FAA M or D airframe data shows little evidence of corrosion as a problem, although information from civil operations led the investigators to believe that corrosion is a serious problem. A report on the Petroleum Helicopters, Inc., maintenance practices (ref. 9) discusses corrosion as a significant problem and states that it is the PHI practice "to get new equipment unpainted and then we do the job ourselves based on experience."

A discussion of the airframe reliability problem is in order at this time. Airframe problems tend to be rather easily detectable well before they become flight safety hazards. Repairs are relatively simple and rapid and have very low associated costs of repair materials. This has two results:

- Malfunctions such as fastener replacement, minor sheetmetal cracking, and corrosion can be repaired before they progress to the hazardous condition requiring an FAA M or D report. Thus the reported airframe malfunction rate based on the FAA M or D reports may not be as representative of the civil helicopter airframe reliability problem as are the dynamic systems, propulsion, drive, and rotor, in which a failure has a more direct association with flight safety and has a greater probability of being reported on the FAA M or D report.
- The cost of repair of failure is low compared to a system involving removal and replacement of an expensive component such as the powerplant or drive. This is the reason for the low repair cost of the airframe subsystem relative to other major subsystems (<1%), as previously shown in Figure 8.

In summary, the airframe failure occurrences are believed to occur at a higher rate than reported on FAA M or D reports simply because of the nonsafety-critical nature of many malfunctions, and this ratio of malfunctions occurring to malfunctions reported is higher than other dynamic systems. The associated maintenance manhours and costs of repair materials

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would also be proportionally more than that shown in this report. Further study of airframe reliability would be in order to prove or disprove this assumption; since airframe malfunction rates on military helicopters with less safety-critical definitions of failure than the FAA M or D report have been reported at over 30 percent of the aircraft rate (ref. 10).

3.2.3 Drive Subsystem. — In terms of total failure rate, the drive subsystem ranks third behind propulsion and airframe as a major civil helicopter problem. However, drive subsystem failures rank first in terms of the requirement for on-aircraft unscheduled maintenance man-hours and second to the propulsion subsystem in terms of cost of repair components and materials associated with the failures.

The severest impact of a drive subsystem failure is caused by an internal failure of the main transmission. To remove a transmission it is necessary (on nearly every helicopter) to remove the rotor hub, blades, and rotor controls. After reassembly, the blade track must be rechecked. Thus, there is a large manhour impact of a transmission malfunction.

The transmission overhaul is sufficiently complex and time-consuming that a small civil operator will use a remove-and-replace technique for an internal malfunction, substituting another transmission while the defective unit is being repaired. This accounts for the high cost of repair components.

The major problems identified for this subsystem and the corresponding detailed technical analysis reference number of the appendix are:

- | | |
|--|------------|
| ● Transmission bearing spalling | Problem D1 |
| ● Tail rotor transmission mount cracking | Problem D2 |
| ● Transmission housing cracking | Problem D3 |
| ● Hanger bearing failure | Problem D4 |
| ● Gear scuffing and spalling | Problem D5 |
| ● Drive shaft spline wear | Problem D6 |

Figure 13 shows the contribution of each of the above major problems to the drive subsystem reliability problem for each of the three reliability parameters of this study (relative frequency of occurrence, unscheduled maintenance manhours, and cost of repair parts). In addition, the drive subsystem impact on the major problems of the entire civil helicopter is given for each reliability parameter for reference.

The dominating drive subsystem major problem is transmission bearing spalling. This problem accounts for over 40 percent of the drive subsystem reported malfunctions, more than 50 percent of the on-aircraft unscheduled manhours associated with drive subsystem reported malfunctions, and over 60 percent of the costs of drive subsystem repair components.

The two other major drive subsystem problems requiring transmission removal and replacement are cracking of the housing and scuffing or spalling of gearing. These problems,

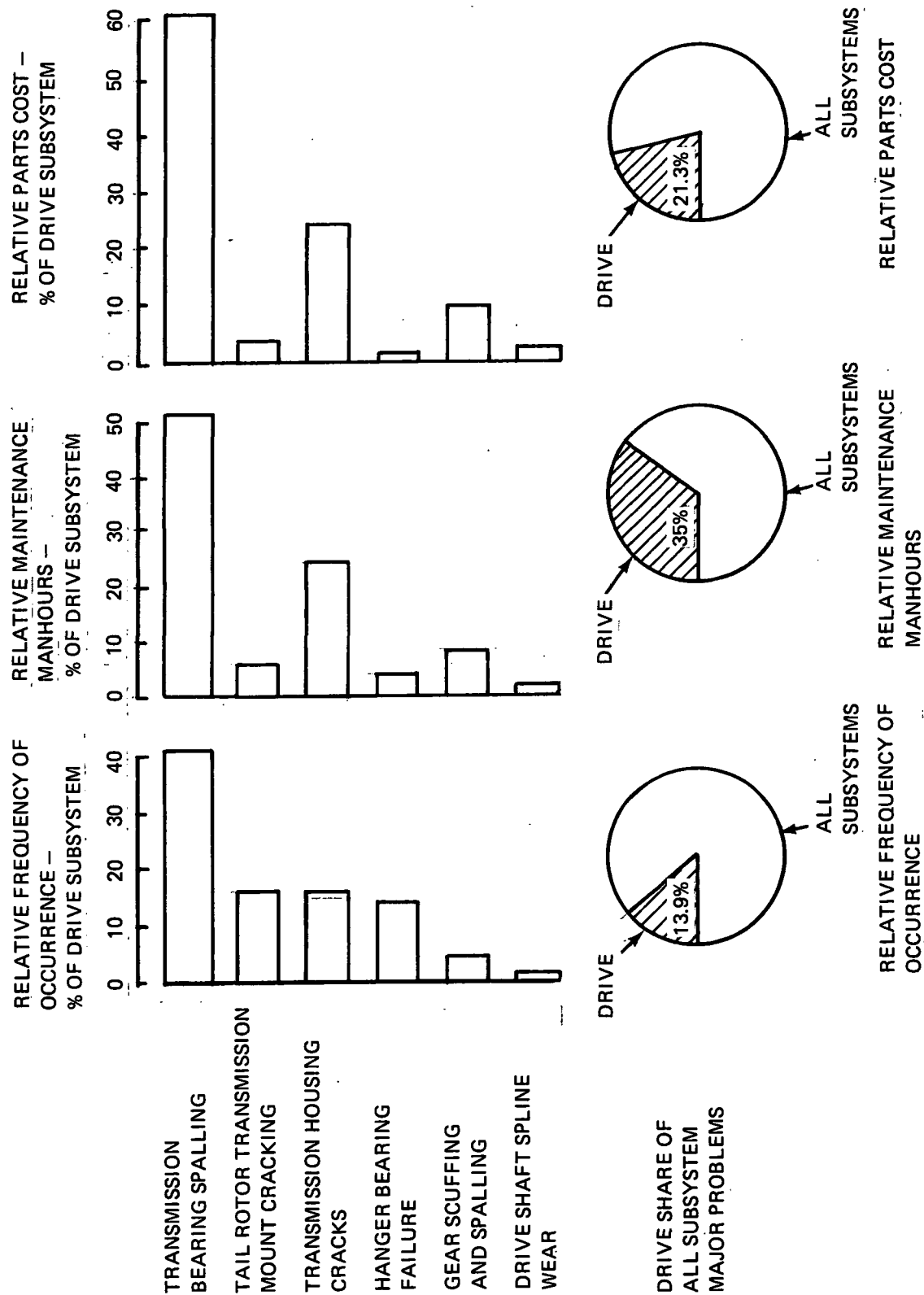


Figure 13. Distribution of drive subsystem reliability problems

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when added to the bearing spall problem, account for 65 percent of drive system reported malfunctions, nearly 90 percent of the maintenance manhours, and 96 percent of the associated repair costs. Clearly, main transmission reliability is a major driving factor in good helicopter reliability.

Investigation showed that bearing spalling is a major problem in the civil helicopter fleet only because of one bearing installation in one model of helicopter and is not a major problem on all models. Cracking of the housing was found to be a similar problem, primarily occurring at one location on one model. These two problems appear to be typical of the state of the art of helicopter transmission design, where the emphasis is on very high power transmittal with very low weight and good efficiencies. An unanticipated load or condition may result in a component malfunction and the correction of a condition of this type will often be technically feasible but require a major component redesign.

Bearing spalling and gear scuffing and spalling are normal forms of deterioration of helicopter transmissions, as is shown by Table 3 which displays detailed military helicopter transmission failure modes. Bearing problems account for 45 percent of the failures, with pitting and spalling accounting for nearly half of the bearing problems. Gear deterioration is responsible for 23 percent of the failures and pitting/scuffing/spall/wear is the largest contributing failure mode. This deterioration is to be expected; however, a condition that exists primarily at one location as reported in the civil helicopter FAA M or D data is a reflection of a detail design problem.

Of the remaining three high-frequency-of-occurrence drive system problems, two were also found to be the result of detail design execution; the third reflects the state of the art.

The tail rotor transmission mount failure is predominantly a one-model-helicopter problem. Hanger bearing failure is also reported as a major problem because of the failure rate occurring with one configuration of tail rotor drive shaft and supporting bearings.

The spline wear problem has been a typical drive system problem and becomes more prevalent when relubrication is difficult and the spline is forced to accommodate misalignment between the coupled members. An improvement in the state of the art of splines, flexible couplings, and lubricants would be of benefit to future helicopter drive systems.

3.2.4 Rotor Subsystem. — The rotor subsystem ranks a close fourth to the drive subsystem in terms of reported failure rate for the major problems. The rotor major problem frequency of occurrence is 12 percent of all aircraft major problems. The associated man-hours to repair rank the rotor as the third highest subsystem at 20 percent of the total; the cost of repair components is also third at 11 percent of total parts cost. Furthermore, although not quantitatively apparent from the civil helicopter data, troubleshooting rotor-system-related vibrations (1 per rev, n per rev) is a major erroneous removal and excessive aircraft downtime problem of military helicopters.

TABLE 3. CHARACTERISTICS OF THE MILITARY DRIVE SYSTEM

Component Element Failure Mode	Distribution (%)	Progression Interval (hr)
Drive System		
Transmissions		
Bearings		
Pitted/spalled	45.21	300
Corrosion		1,000
Fracture/broken cages		10
Seizure (no lube)		1
Worn races and rolling elements		1,000
Gears		
Pit/scuff/spall/wear	23.23	200
Corrosion		1,000
Mount flange crack		200
Teeth fracture		20
Fretting		800
Spline wear		900
Lube System (Coolers/fans,lubricators)		
Corrosion	3.24	800
Leaking		100
Wear		400
Broken studs, lines, etc		25
Seizure of pump/fan		11
Retention and Mounting Hdw		
Pitted/broken	16.00	500
Corrosion		1,000
Wear		800
Nonrotating Structure		
Corrosion	5.08	1,000
Wear		300
Broken/chipped		250
Cracked		700

TABLE 3 - Continued

Component Element Failure Mode	Distribution (%)	Progression Interval (hr)
Clutches		
Corrosion	3.25	0.33 1,000
Seizure		0.002 1,000
Wear		1.5 300
Spline wear		0.48 600
Broken clips		0.79 100
Cracked		0.15 1
Shafts (quill and gear)		
Pitted/spalled splines	4.00	0.75 600
Corrosion		0.49 1,000
Fatigue cracking		0.20 10
Worn splines		2.55 500
Shafting		
Sync Shafts/T/R Shafts		
Cracked	6	2.0 10
Misaligned		2.0 500
Dented		1.0 100
Scored		1.0 25
Hanger Assembly		
Bearing wear/spall	36	24.0 200
Leaking		8.0 200
Lube starved		4.0 20
Mounts		
Broken	25	22.0 100
Cracked		3.0 150
Adapters		
Lug failures	16	3.0 25
Improper alignment		10.0 300
Spline wear		3.0 300
Couplings		
Broken/cracked	17	12.0 25
Bolt failures		1.0 25
Bent		2.0 200
Worn		2.0 200

Transmission data from USAAMRDL TR73-58
Shafting data from Boeing document D210-10846-1

The subject of fault-isolating the source of unusual vibration is addressed in the maintenance report (ref. 11) generated by this study.

The major problems identified for this subsystem and the corresponding detailed technical analysis reference numbers of the appendix are:

- | | |
|------------------------------------|-------------|
| ● Blade cracks and corrosion | Problem R1 |
| ● Tension-torsion assembly failure | Problem R2 |
| ● Swashplate support cracking | Problem R3 |
| ● Rotor hub bearing failure | Problem R4 |
| ● Main rotor retention nut failure | Problem R5 |
| ● Tail rotor grip bearing failure | Problem R6 |
| ● Swashplate bearing failure | Problem R7 |
| ● Main rotor mast corrosion | Problem R8 |
| ● Rotor hub seal leaks | Problem R9 |
| ● Rotor hub corrosion | Problem R10 |

Figure 14 shows the contribution of each of the above major problems to the rotor subsystem reliability problem for each of the three reliability parameters of this study (relative frequency of occurrence, unscheduled maintenance manhours, and cost of repair parts). In addition, the rotor subsystem impact on the major problems of the entire civil helicopter is given for reference.

Cracking and corrosion of blades and failures of the tension-torsion assembly constitute the two highest ranking rotor subsystem problems in terms of relative failure frequency and the cost of repair/replace components. The tension-torsion assembly problem has the highest unscheduled maintenance manhour requirement of the rotor subsystem.

The remaining problems individually are of relatively low failure rate, associated maintenance manhours, and cost of repair parts but in aggregate constitute a significant problem. As discussed in more detail in the individual writeups, these problems are primarily due to the state of the art in design execution for an area exposed to loads of a variable magnitude and vibratory nature, with sand, dust, and rain environment, and subject to frequent maintenance operations which increase the chance of Murphy-type errors.

3.2.5 Landing Gear Subsystem. — There is a great difference in the landing gear problems encountered by civil and military helicopter operators. A comparison of failure modes experienced by the two operators is shown below:

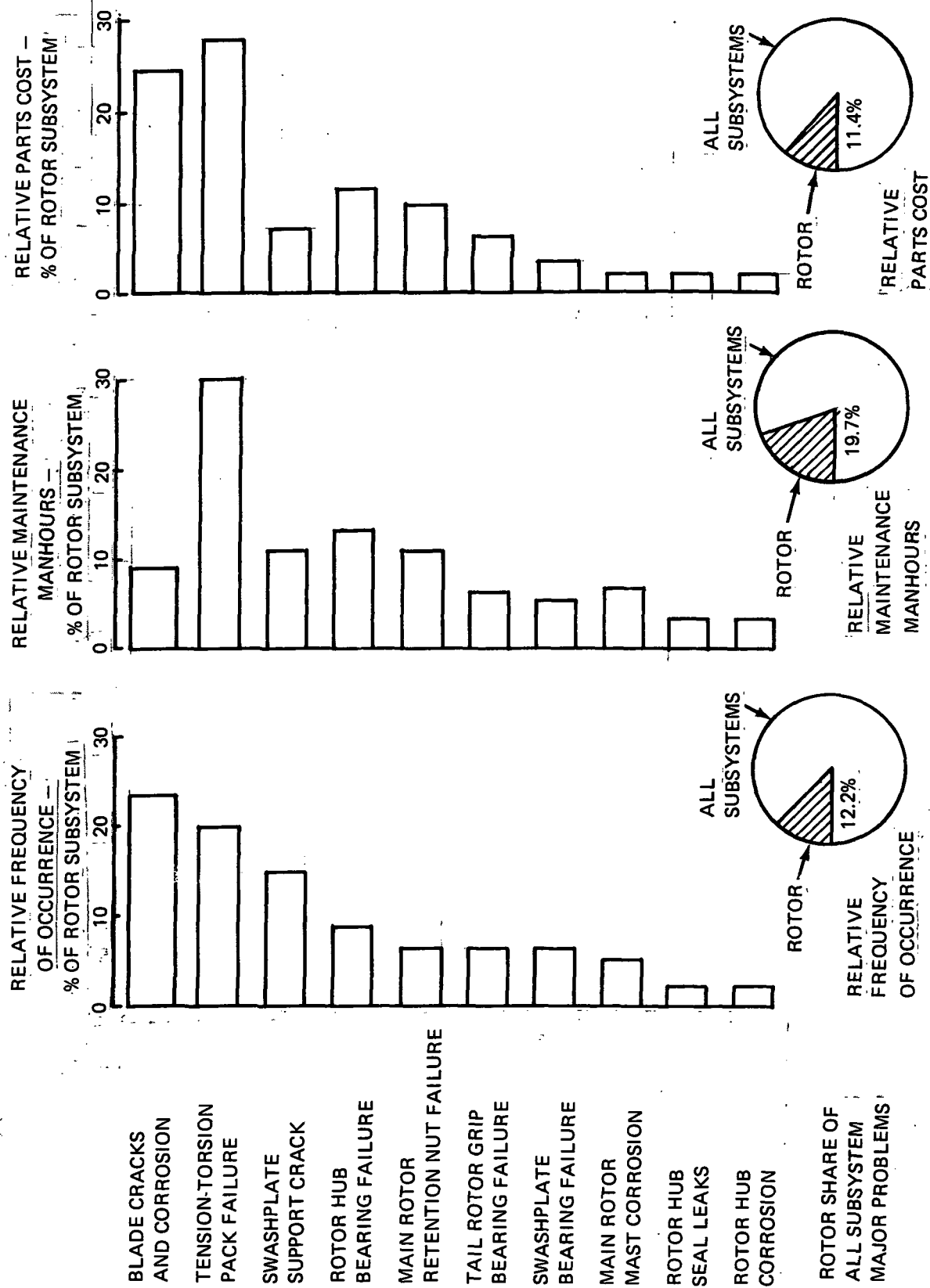


Figure 14. Distribution of rotor subsystem reliability problems

Civil Operator

- Popout/fixed flotation gear leakage
- Structure, cross-tube cracks
- Broken skid

Military Operator

- Wheel bearings rough, broken
- Brakes worn or cracked
- Strut worn, leaks
- Master cylinder leaking
- Parking valve failure
- Skid, cross-tube failure

Float leakage is the only landing gear problem on the civil helicopter major reliability problem list but is the third largest reliability problem in terms of the frequency of reported failures for the period monitored, 1971 through 1976.

The extensive use of flotation gear by helicopters performing offshore oil-drilling support raised this problem to a magnitude unparalleled by military landing gear problems. Simultaneously, the civil operators' general preference for skid-type gear rather than wheels (especially for oil platform operation) negated the major military problems related to wheels, brakes, and master cylinders. The impact of this problem on the civil helicopter reliability problem in terms of the three reliability parameters of this study (relative frequency of occurrence, unscheduled maintenance manhours, and the cost of repair parts) is given in Figure 15. This problem is discussed in more detail in the appendix, reference number L1.

Further investigation of the float leakage problem showed that an aggressive product improvement program had been conducted by a major float manufacturer midway through the reporting period in response to the magnitude of the reported problem. After these changes had been implemented, the reported failure rate dropped by a factor of 10 to 1; with the lower malfunction rate, float leakage was no longer on the major reliability problem list.

This was not apparent from the data review until a year-by-year study of reported failures was made. When this was done, a rather dramatic drop in reported failures could be observed in the period following the introduction of the float improvements.

Following examination of the FAA M or D data and the reported failure modes, a preliminary report of this problem was discussed with a representative of the Air Cruisers Company, Division of the Garrett Corporation, a major float manufacturer. In brief, the Air Cruisers Company stated that they had been alerted by the Helicopter Association of America and two helicopter manufacturers of reported problems. They took the following steps:

- Identified the problem modes and causes by:
 - Discussion with the helicopter manufacturers.
 - Discussion with the float-using operators.
 - Review of the FAA M or D reports submitted by the HAA.

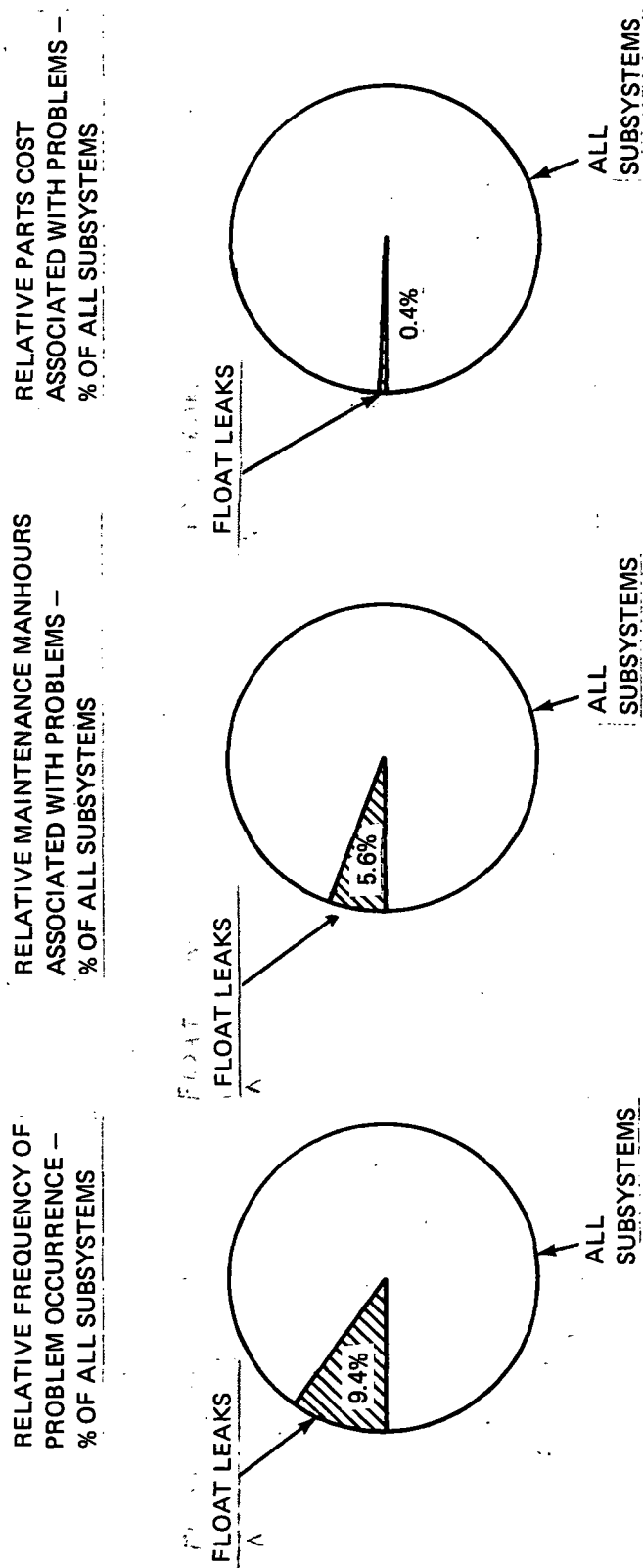


Figure 15. Relative reliability of landing gear subsystem (float leaks)

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- Instituted an immediate short-range program to reduce problems, primarily to assure the proper inspection, maintenance, and operational procedures since floats are extremely sensitive to any deviations from anticipated design conditions in these areas. This is particularly true in terms of inflation practices and prevention of chafing and abrasion.
- Instituted a longer-term program to increase float performance in the present operational environment. This includes the following:
 - Increased thickness of coatings on the float fabric.
 - Reinforcement to wear areas.
 - Testing and making available to operators a top dressing to improve weather resistance.
 - Reviewed and clarified maintenance manuals which define proper care of floats.
 - An in-house review of manufacturing practices to assure that this was not contributing to the reported failures.
 - Other detailed investigations and changes in the areas of fungus resistance, adhesive and solvent compatibility of float materials, and structural improvement.

That this program was effective is indicated by the HAA records of FAA M or D reports which show, on one model helicopter, 105 float reports submitted in the 2-year period 1973 and 1974, and only 5 in 1975.

It is significant that the original floats were reported to meet the helicopter manufacturers' specifications in all respects. The floats incorporating the long-range improvements carried a weight penalty of approximately 20 percent in achieving the improved reliability.

The history gives an indication of the reliability improvement possible in some areas if problems are vigorously attacked and realistic weight/reliability trades are adopted.

3.2.6 Hydraulics Subsystem. — In the military environment, line and hose leaks dominate the hydraulic system failure rate. This has led the industry to design helicopters with modular hydraulic systems wherein the number of potential leak points is greatly reduced. Line/hose leaks are also a problem to the civil operator, but not to as great an extent as the military.

Flight control actuator/servo leakage is the only hydraulic subsystem problem in the civil helicopter major reliability problem list. Figure 16 shows the impact of the hydraulic subsystem, and thus this problem, on the major problems of the civil helicopter in terms of the three reliability parameters of this study (relative frequency of occurrence, unscheduled maintenance manhours, and cost of repair parts). This problem accounts for approximately 4 percent of the reported failures, less than 3 percent of the associated manhours for an on-aircraft repair, and approximately one-tenth of one percent of the cost of repair/replacement components. The problem is fundamentally one of seal technology (ref. 12). It appears that

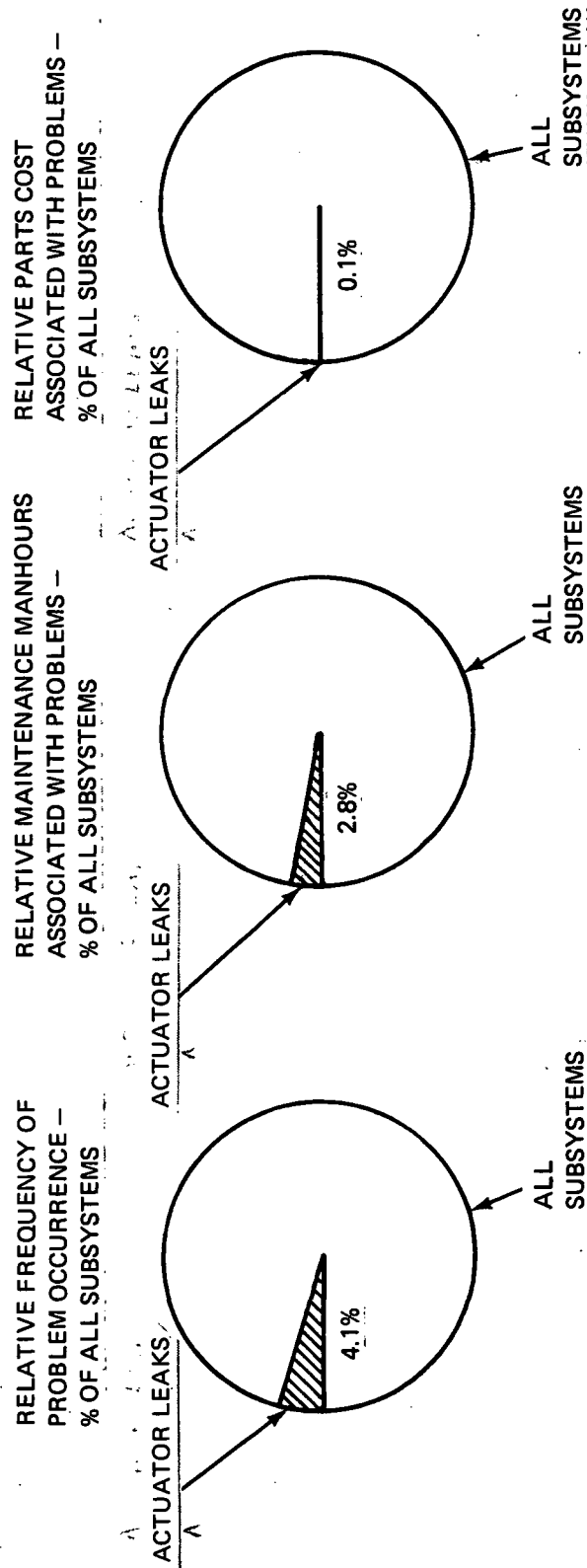


Figure 16. Relative reliability of hydraulic subsystem (actuator leaks)

the reported problem is to a large degree solvable by existing technology, as the frequency of problem occurrence on one model of helicopter has driven this problem to the major reliability problem list. The problem is discussed in greater detail in the appendix, reference number H1.

3.2.7 Fuel Subsystem. — The fact that three fuel subsystem problems are members of the top reliability problem list is of some surprise to a reliability engineer accustomed to reviewing military helicopter data. These three problems and the corresponding detailed technical analysis reference number of the appendix are:

- | | |
|---------------------------------|------------|
| ● Fuel pressure switch problems | Problem F1 |
| ● Fuel pump failure | Problem F2 |
| ● Fuel cell leakage | Problem F3 |

The fuel subsystem major problems account for 5 percent of the civil helicopter reliability problem in terms of the frequency of occurrence of a problem, but account for only 1 percent of the unscheduled maintenance manhours and less than one-half percent of the cost of repair components associated with these failures.

Figure 17 shows the contribution of each of these three problems to the entire fuel subsystem problem in terms of each of the three reliability parameters of this study (relative frequency of occurrence, unscheduled maintenance manhours, and the cost of repair parts). In addition, the fuel subsystem impact on the major helicopter reliability problems is given for each parameter for reference.

Failure of fuel pressure switches is the most frequently occurring problem and responsible for the largest maintenance manhour expenditure on this subsystem. Fuel cell leakages cause the largest impact on repair parts costs. Fuel pump problems have the second highest frequency of malfunction and are second highest in terms of maintenance manhours.

The solution of all fuel system problems would benefit from a better definition of failure modes and causal factors. A review of problems to date has indicated that all three problems can be alleviated by better application of current technology:

- Fuel pressure switch failures are partially due to the lack of design consideration for the helicopter maintenance and vibratory environment.
- The fuel boost pump failures are believed to be predominantly direct-current-powered units; Boeing Vertol experience has been that the newer ac-powered motor pumps have an appreciably improved reliability.
- Fuel cell problems can be alleviated by better design for the aircraft maintenance and operational environment.

More detail on these problems is given in the detailed technical discussion in the appendix.

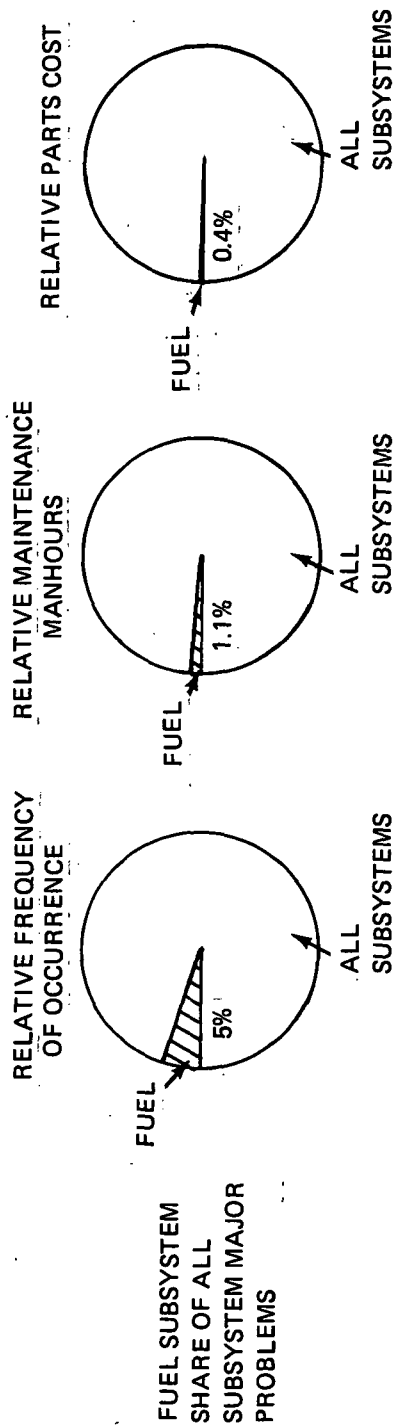
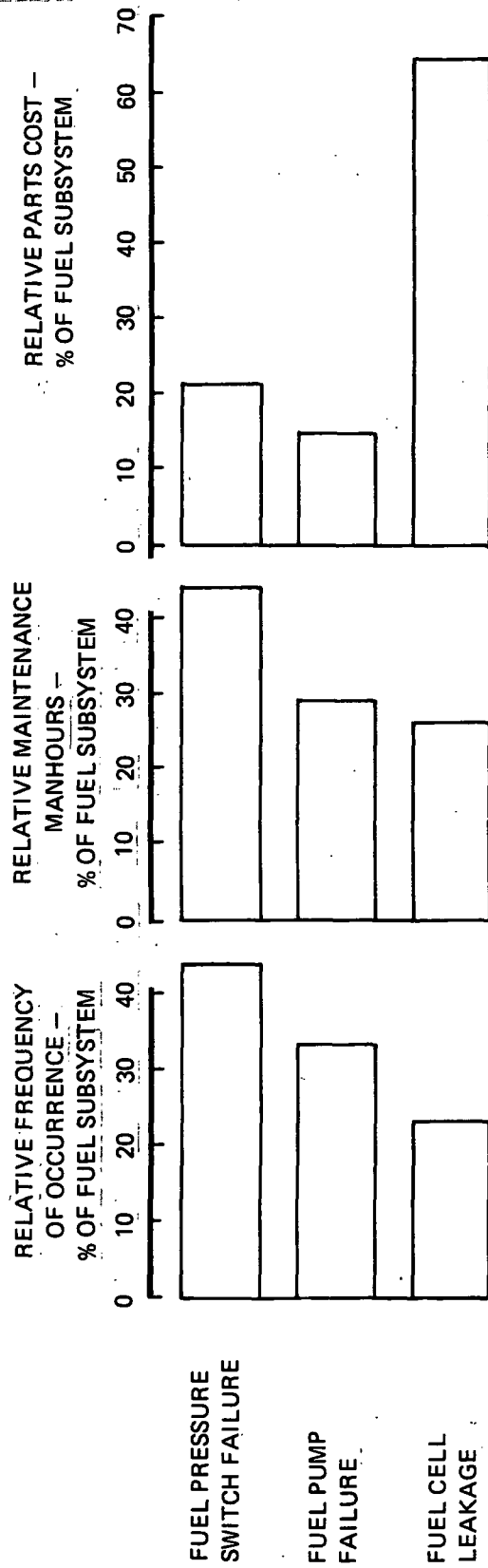


Figure 17. Distribution of fuel subsystem reliability problems

3.2.8. Remaining Systems. — None of the flight control, instrument, or electrical subsystem problems were of a sufficient magnitude to be members of the civil helicopter top reliability and maintenance cost problem lists. These systems represent only 5 percent of the total problems and are nearly equal in occurrence. Some of the more significant problems in these subsystems are listed below.

Instrumentation/Avionics (1-2/3% of total)

Engine gas temperature indicator (32% of this subsystem's problems)

Bulbs (29% of this subsystem's problems)

Transducers (23% of this subsystem's problems)

Tachometers (16% of this subsystem's problems)

Flight Controls (1-2/3% of total)

Tail rotor chain (42% of this subsystem's problems)

Binding or loose linkage (39% of this subsystem's problems)

Electrical (1-2/3% of total)

Generator (40% of this subsystem's problems)

Battery (charge and overheating) (33% of this subsystem's problems)

Anticollision light (13% of this subsystem's problems)

All three of these systems are significant contributors to the mission abort and troubleshooting problems associated with helicopters. However, the quantification of these problems from the FAA M or D reports is impossible as the abort and troubleshooting data is not included. The problem of mission aborts is discussed in the following section.

3.3 Mission Reliability

The FAA M or D report provides no information with regard to mission reliability, and so neither the magnitude nor the source of the mission abort problem could be determined for the civil helicopter fleet.

Data on mission aborts for the OH-58 helicopter is available (ref. 7). This is the military counterpart of one of the most widely used civil helicopters, the Bell Model 206. The magnitude and source of the problem experienced by the military are an indication of the importance of mission reliability to civil helicopter fleets.

Table 4 shows the magnitude of the military helicopter abort problem. Only three of every 10,000 flights are not completed because of a hardware-oriented problem.

Table 5 gives the source (responsible subsystem or component) of the mission aborts and also shows the comparative hazard of the failure in terms of a precautionary landing incident, forced landing, or major or minor accident. The dominant source of mission aborts is warning lights. This subject requires additional research to determine if the civil operator has this

problem. The second major source of mission aborts is engine failures. Engine failures have the highest percentage of hazardous aborts, resulting in one-third of the major accidents, over 40 percent of the incidents, and nearly three-quarters of the precautionary landings.

Figure 18 displays the causes of engine aborts for two turbine engines used in fixed-wing applications. The dominant mode of failure is (as it is for civil helicopter engines) fuel control and governing devices.

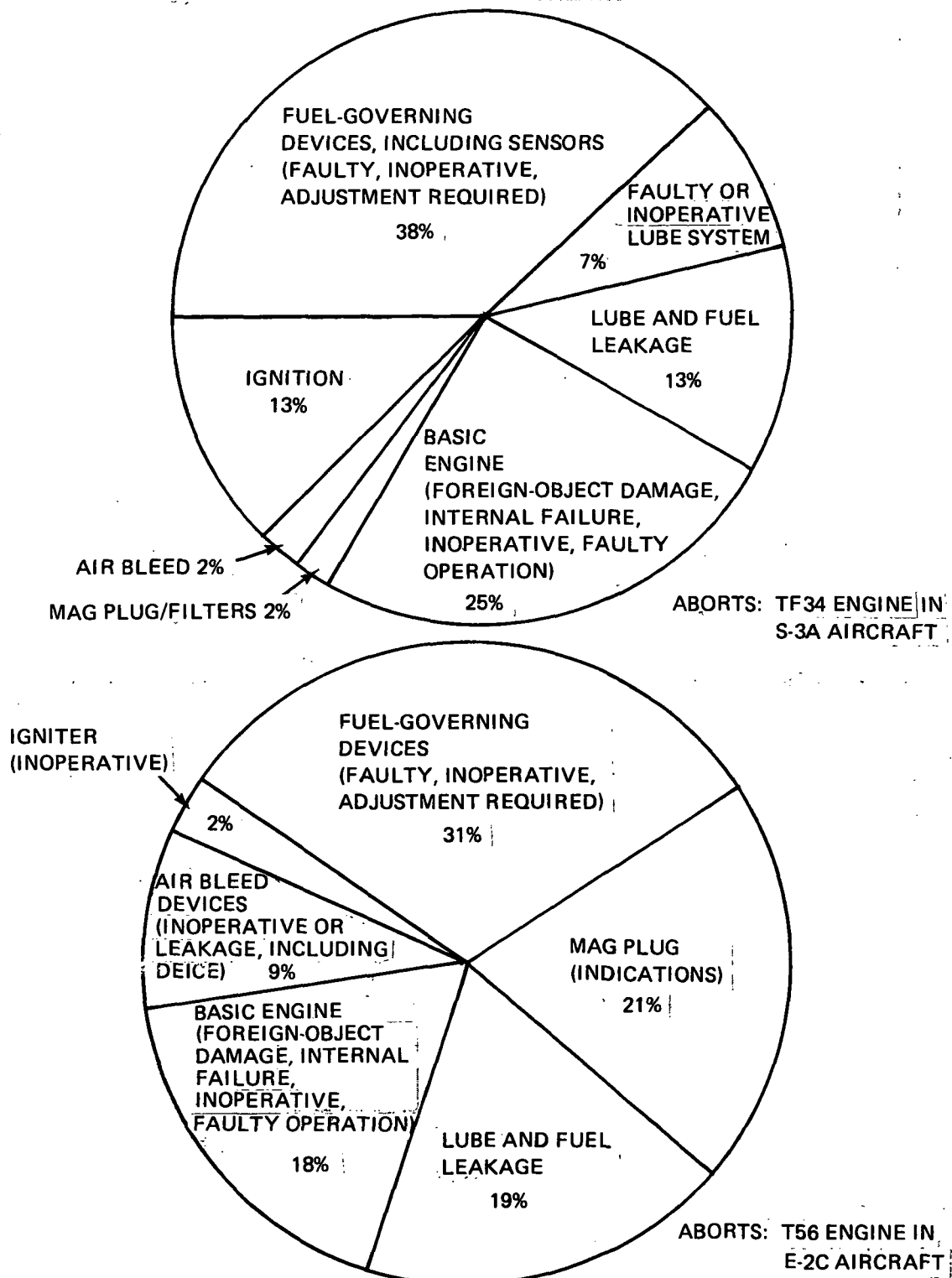
Reference 7 states that 13 percent of mission aborts are caused by false indications of the warning light system. However, three quarters of the aborts which resulted in a major or minor accident, forced landing, or incident originated from a malfunction of one of the major problem area subsystems covered in this report. It is believed by the authors that the entire subject of civil helicopter mission reliability requires additional research. The recommended product improvements and research and development of this report will, however, have a substantial impact in reducing civil helicopter mission aborts.

TABLE 4. FLIGHT SUCCESS OF THE OH-58A HELICOPTER,
AUGUST 1970 THROUGH JUNE 1972

Statistic	Location		Totals
	Within CONUS ¹	Outside CONUS ¹	
Number of Flights	681,572	1,000,275	1,681,847
Average Flight Duration (minutes)	16.037	21.023	19.003
Number of Flight Aborts	188	318	506
Flight Success (percent)	99.973	99.968	99.970
Accrued Flight Hours	182,173	350,487	532,660
MTB Flight Aborts (flight hours)	969.005	1,102.16	1,052.668
NOTES: 1. CONUS = Continental United States 2. Number of flights, number of landings, accrued flight hours, and total flight hours reported on DA Form 1352 3. Flight duration (minutes) = $\frac{\text{accrued flight hours}}{\text{no. of flights}} \times 60$ 4. Flight success % = $(1 - \frac{\text{no. of flight aborts}}{\text{no. of flights}}) \times 100$ 5. From reference 7			

TABLE 5. ARMY OH-58A DATA ON ITEMS MOST FREQUENTLY CAUSING FLIGHT ABORTS, AUGUST 1970 THROUGH JUNE 1972

Category Cause	Precautinary Landing	Incident	Forced Landing	Major Accident	Minor Accident	Total Loss	Total by Cause	No. of Hardware- Caused Aborts (%)
Warning Light	170		3				173	50.3
Engine Failure	14	6	36	6			62	18.0
Instrument Indication	17		2				19	5.5
Hydraulic System	17			1			18	5.2
Fuel System	6		4	1			11	3.2
Control System	6		1	2		1	10	2.9
Tail Rotor	5	1		3			9	2.6
Excessive Vibration	6	2		1			9	2.6
Electrical System	7						7	2.0
Gearbox	4			3			7	2.0
Main Rotor System		5		1	1		7	2.0
Instrument Failure	5						5	1.5
Hanger Bearing Failure	3		1				4	1.2
Oil System Failure	1		2				3	0.9
Totals	261	14	49	18	1	1	344	100.0
From reference 7								



FROM NAVY 3M DATA, JANUARY 1975 THROUGH NOVEMBER 1976

Figure 18. Distribution of engine subsystem reliability problems on U.S. Navy aircraft

The major subsystem reliability problems were reviewed to see which could be alleviated by application of present technology and which required additional research and development for any substantial reliability improvement. Table 6 gives an estimate of the percentage of the reliability problems of each subsystem that require each of the two categories of action. As shown in Table 6, solution of propulsion subsystem reliability problems is highly dependent on additional R&D, while the other major subsystems – airframe, drive, and rotor – have a slightly higher percentage of problems that are solvable by product-improvement-type changes than those requiring additional R&D for solution. The landing gear, fuel, and to a lesser degree, the hydraulic subsystem problems are largely solvable with product-improvement-type changes.

Table 7 gives a brief summary of the failure modes and the nature of the recommended action to improve the reliability for each major problem, either in terms of a product-improvement-type change or the recommended R&D program. The backup discussion of each problem is contained in the problem writeup in the appendix.

As can be seen from the detailed problem writeups and the recommended action, this study defined product-improvement-type changes using present technology as having a great potential for alleviating the civil helicopter reliability problem. The difficulties of implementing these changes should not be underemphasized. Solution of some problems requires extensive redesign which affects other interfacing components. Requalification of components is needed, which is both expensive and time-consuming. Component weight and cost may be adversely affected. Service manuals, spares costs, and similar factors may add up to such a high price that retrofit incorporation of a change just for increased reliability may not be cost-effective in the existing civil helicopter fleet. It may well be the subject of a study to determine how to establish incentives for incorporation of product-improvement reliability changes; perhaps a reliability warranty program could be examined.

TABLE 6. TYPE OF ACTION REQUIRED FOR RELIABILITY IMPROVEMENT

Subsystem	Estimated Percentage of Problems Solvable With Present Technology	Estimated Percentage of Problems Requiring R&D for Solution
Propulsion	10	90
Airframe	60	40
Drive	50	50
Rotor	60	40
Landing Gear	90	10
Hydraulic	60	40
Fuel	80	20

TABLE 7. RELIABILITY IMPROVEMENT ACTION

Subsystem/Component	Failure Modes	Action, R&D Program Definition
Propulsion Subsystem Fuel Control and Fuel Governors	Improper starting (hung starts)	A joint airframe/engine manufacturer effort is required to determine cause/resolution of fuel control/governor problems.
	Speed fluctuations	
	Erroneous removal (no defect)	A field diagnostic/inspection technique for fault-isolating fuel control/governor-related problems is required, to minimize the frequency of erroneous removals. One option to be considered is the development of a field level GSE item for off-aircraft fuel control/governor checkout.
	Improper operation resulting from contamination (military engines, ref. 8)	Program for fleet evaluation of reliability with improved filtration of fuel and fuel control actuating media.
Compressor Failures	Predominant mode listed as "failure". Military helicopter engines list FOD as major cause of compressor failure.	A joint airframe/engine manufacturer effort is required to determine cause/resolution of compressor problems.
		Revision of FAA M or D report to request additional data on failure causes be supplied by engine overhaul facilities.
		Engine inlet screen effectiveness evaluation.
Engine Lubrication System	Pumps/check valves, coolers, filters, tubing, fitting failures. Contamination is an important contributor (military engines, ref. 8).	A joint airframe/engine manufacturer effort is required to determine cause/resolution of lube system problems.
		Program for field evaluation of engine reliability with improved filtration of lubrication system
Fuel Pump Spline	Excessive spline wear	The problem can be greatly alleviated by a product improvement program without additional R&D.
		Implement a program to supplement military programs addressing the spline wear problems.

TABLE 7 - Continued

Subsystem/Component	Failure Modes	Action, R&D Program Definition
Propulsion (continued) Turbine Failures	Predominant failure mode listed as "failure". Military helicopter engines are reported to have nozzle problems (ref. 8).	A joint airframe/engine manufacturer effort is required to determine cause/resolution of turbine problems. A materials/coatings development program to improve nozzle life will alleviate the turbine failure problem.
Airframe Skin and Structure	Cracks, failure	Study to define design specifications for the real maintenance and user environment. Program to design, manufacture, and field test composite skin and structure as given in reference 3. Program to reduce vibration levels; one method would be to develop and field test a vibration isolation system as given in reference 2.
Small Hardware	Loss or failure (Causes of military helicopter hardware problems given in ref. 13 are: Vibration-induced, maintenance damage, manufacturing tolerances)	Study to define specifications for the real maintenance and user environment. Program to field test an airframe reinforced at hardware attach points and having maintenance/user-resistant hardware properly installed. Fastener research for larger tolerance to discrepant maintenance and improper manufacturing tolerances. Hardware research for composite structure compatibility. Program to reduce vibration levels (ref. 2).

TABLE 7 - Continued

Subsystem/Component	Failure Modes	Action, R&D Program Definition
Airframe (continued)		
Skin Unbonding	Delamination of (predominantly) metal-faced honeycomb panels from improper manufacturing procedures, hygroscopic bonding materials, improper panel sealing, and mechanical damage such as punctures	A field program is recommended to demonstrate the reliability improvement possible with present technology of composite honeycomb panels. A study to define design requirements to survive in the real operational and maintenance environment. This would include damage-tolerance requirements and a definition of performance (supported by testing) of honeycomb panel skins of different materials and thicknesses. A study/test program to define methods of fastener and structural attachments to composite honeycomb panels. An advanced composite honeycomb panel design program as defined in reference 3.
Drive		
Transmission Bearings	Spalling (Magnitude of problem results largely from the failures occurring to one bearing in one model helicopter; the generic spalling problem is of much smaller magnitude but a prevalent helicopter transmission problem)	Specific problem solution appears to be a product-improvement-type redesign, not an R&D program. Generic spalling problem: Product-improvement-type changes to incorporate recent developments in materials, control of bearing characteristics, and weight/load/cost reliability-type trades will reduce the magnitude of this problem.

TABLE 7 - Continued

Subsystem/Component	Failure Modes	Action, R&D Program Definition
Drive (Continued)		A state-of-the-art lubricants program is recommended to consist of preliminary screening tests to assure safety of flight, followed by field demonstration of the bearing life improvement resulting from the use of better transmission lubricants. Continued research into bearing materials to improve load-carrying characteristics and into transmission housing materials to increase stiffness (ref. 1). Vibration reduction programs described in reference 2 will reduce the magnitude of unanticipated loads on the bearings. The specific problem resolution appears to be a product-improvement-type redesign, not an R&D program. Cost-effectiveness of problem correction might be aided by reliability warranties so that the operator does not assume the complete burden of this type of failure. A vibration reduction program oriented to the tail rotor area and addressing the vibration reduction approaches given in reference 2 would reduce the unanticipated loads causing this type of helicopter reliability problem. The specific problem resolution appears to be a product-improvement-type redesign, not an R&D program. Cost-effectiveness of problem correction might be aided by a reliability warranty program. Continued research into rotor loads and vibration reduction as outlined in reference 2 should alleviate this problem.
Tail Rotor Transmission Mounting	Cracking, failure (Note: Magnitude of the problem results largely from the failures occurring to the mounting of one model helicopter. It is not a generic problem to the civil helicopter.)	
Transmission Housing	Cracking in the attach, lift lugs (Note: The magnitude of this problem results largely from the failures occurring to the main transmission mounting of one model helicopter. It is not a generic problem to the civil helicopter.)	

TABLE 7 - Continued

Subsystem/Component	Failure Modes	Action, R&D Program Definition
Drive (continued) Hanger Bearing	Failure	The specific problem resolution appears to be a product-improvement-type redesign, not an R&D program. Cost-effectiveness of problem correction might be aided by a reliability warranty program. In general, somewhat complex approaches to hanger bearing design, incorporating bearing relubrication provisions and flexible couplings, have increased reliability with adverse effect on initial cost and weight. A program to determine the life-cycle cost impact of these factors would put this problem in proper perspective. This should be part of any product-improvement program.
Gear Deterioration	Scuffing, spalling	As recently developed materials and improvements in process controls give much improved performance in terms of scuffing and spalling, a product-improvement program to incorporate the latest materials developments and manufacturing/quality controls on gear processing would do much to alleviate this problem. Cost/weight reliability trades would do much to put this problem in proper perspective. These programs might be conducted in conjunction with a similar program on transmission bearings. A state-of-the-art lubricants program is recommended to consist of preliminary screening tests to assure safety of flight, followed by field demonstration of the gear spalling life improvement resulting from the use of better transmission lubricants. This could be a joint bearing/gear program.

TABLE 7 - Continued

Subsystem/Component	Failure Modes	Action, R&D Program Definition
Drive (continued)		
Gear Deterioration (continued)	Scuffing, spalling (continued)	A program to improve load-sharing of gear teeth, reduce sliding, and other improvements as identified in reference 1. A program to develop improved transmission lubricants. This should apply to both gearing and bearings.
Drive shaft splines	Wear (Note: The magnitude of this problem results largely from a specific design configuration incorporating a flexibly mounted transmission and an engine separately mounted on the airframe. The drive shaft splines thus accommodate considerable axial motion and misalignment. The spline wear problem is generic at a somewhat lower rate.)	The specific problem resolution is a product-improvement-type redesign, not an R&D program. The most promising area of specific problem resolution appears to be a grease lubrication system for the splines that can be done on the aircraft without disassembly. Two areas of research are beneficial: 1. Development of improved flexible couplings will reduce the spline requirements. 2. Development of improved lubricants for splines, including the use of dry lubricant materials. With the increasing use of rotor-isolation systems, the spline wear problem is becoming more acute.
Rotor		
Metal Blade	Cracking and corrosion	Fiberglass composite blade construction has shown improved reliability over metal blades in respect to cracking and corrosion. Fleet incorporation of fiberglass blades is not R&D dependent but a product-improvement-type change that must balance the costs of redesign against any potential saving in operating cost due to increased reliability.

TABLE 7 -- Continued

Subsystem/Component	Failure Modes	Action, R&D Program Definition
Rotor (continued)		
Metal Blade (continued)	Cracking and corrosion (continued)	A program is recommended to develop an advanced composite blade for future helicopters to optimize blade deflection, weight, and strength characteristics and retain R&M characteristics similar to fiberglass (ref. 3).
Tension-Torsion Assemblies	Deterioration, failure (Note: The magnitude of this problem results from a specific method of blade centrifugal retention; multiple windings of high-strength wire. Deterioration of this wire pack causes this assembly to be a major reliability problem.)	The specific problem resolution is a product-improvement-type redesign as other design approaches for blade retention are available which have shown excellent reliability characteristics. A weight/cost/reliability trade may be necessary. No R&D effort required.
Hub and Swashplate Support	Cracking (Note: The magnitude of this problem results from malfunction in a few of many similarly designed components.)	Programs for development of bearingless rotor hubs are under way. These hubs use a torsionally flexible composite structure to replace tension-torsion assemblies as well as rolling-element bearings and their lubrication system. Continued development of these hubs is recommended.
		The specific problem resolution is a product-improvement-type redesign as other similar components do not experience these failures. Cost-effectiveness of problem correction might be aided by a reliability warranty program.
		Continued research into rotor loads and vibration reduction as outlined in reference 2 should alleviate this problem.

TABLE 7 - Continued

Subsystem/Component	Failure Modes	Action, R&D Program Definition
Rotor (continued)		
Hub Bearings	Failure	Increased reliability is primarily a cost/weight/reliability trade for these bearings. Incorporation of larger bearings in a product-improvement-type change would adversely affect weight and cost but result in increased reliability. Development of the bearingless main rotor, with flexing elements rather than rolling-element bearings, eliminates two of the three troublesome applications. A program is recommended for continuing the development of the technology of elastomeric and dry lubricant (such as TEFLON* fabric) bearings. The design parameters for helicopter oscillating applications with combinations of alternating and steady loads are not available to the helicopter or bearing designer.
Main Rotor Retention Nut	Failure (Not adequately defined)	The specific problem resolution is a product-improvement-type redesign as other similar applications have hardware that is performing reliably. A program to define material and process control characteristics of critical dynamic system helicopter hardware would be beneficial since standard hardware heat-treated in the brittle range fails due to material and process flaws at such a frequency as to constitute a generic problem from a safety, if not a reliability viewpoint. This is also a product-improvement-type program. A program to develop redundant hardware for helicopter dynamic and flight controls systems would be of value. Such an approach has been used for over a decade in the commercial air transport flight controls systems.

*Registered trademark of E. I. du Pont de Nemours, Wilmington, Delaware

TABLE 7 -- Continued

Subsystem/Component	Failure Modes	Action, R&D Program Definition
Rotor (continued)		
Tail Rotor Grip Bearings	Failure, wear	The specific problem resolution is a product-improvement-type redesign rather than an R&D program. Bearingless hubs should be considered for any product-improvement redesign. A program for development of the technology of TEFLON fabric and (as a possible replacement for this application) elastomeric bearings would assure that future helicopter designers would have the design information needed to assure long life in these bearing applications.
Swashplate Bearing Failures	Deterioration, failure primarily in dry lubricant-type bearings for swashplate and support system	Problem resolution requires product-improvement-type redesign. Recent concepts of swashplate support and centering permit bearing replacement without blade and hub removal, thus making a significant reduction in MMH associated with this problem. A program for further development of the technology of TEFLON fabric and other dry lubricant bearings, as well as elastomeric bearings, would aid in life prediction of future bearings of this type and so reduce the magnitude of this problem in future helicopters.
Main Rotor Mast	Corrosion, causal factors poorly defined in data base. Maintenance damage a contributor on military helicopters.	Problem resolution is a product-improvement-type redesign using coatings with more corrosion resistance and damage tolerance, as well as mast materials with more damage tolerance. These approaches require a cost/weight/reliability trade.

TABLE 7 - Continued

Subsystem/Component	Failure Modes	Action, R&D Program Definition
Rotor Hub	Seal Leakage	This is a generic helicopter problem with some improvement possible by improved material and process control in product-improvement-type changes. The following R&D programs will alleviate this problem: - o A program to determine design parameters for oscillating seals. - o A program to evaluate flexible boot-type seals. - o Development of elastomeric and other sealless bearings. - o Development of bearingless rotor hubs.
Rotor Hub	Corrosion, causal factors poorly defined in data base. Maintenance damage is a contributor on military helicopters.	Problem resolution is a product-improvement-type redesign using coatings with more corrosion resistance and damage tolerance. Development of the composite bearingless hub will reduce the impact of environmental and maintenance damage (ref. 14).
Landing Gear Floats	Leaking	Float reliability was dramatically improved toward the end of the period reviewed by a comprehensive product-improvement program. Further gains can be made with present technology by continued development of this type. A program for materials and structural technology R&D is recommended for long-term float reliability gains.

TABLE 7 - Continued

Subsystem/Component	Failure Modes	Action, R&D Program Definition
Hydraulics		
Flight Control Actuator	Seal Leaking	Product-improvement-type changes using present technology will reduce the seal leakage problem. A seal/filtration R&D program is recommended for future helicopter reliability improvement.
Fuel Subsystem		
Fuel Pressure Switch	Failure (causal factors poorly defined in data base)	A study of causal factors followed by a product-improvement-type program will alleviate this problem.
Fuel Pump	Failure (causal factors poorly defined in data base)	A study of causal factors is needed and a trade study to determine the applicability of ac-powered motor pumps should be made, following which product-improvement-type changes will alleviate this problem.
Fuel Cell	Leakage caused by mechanical damage, chafing, and delamination	Failure causes are fairly well-defined and product-improvement-type changes (possibly involving a weight/cost/reliability/trade) will alleviate the problem. An R&D program to develop improved materials for this application is recommended to improve fuel cell reliability in future helicopters with minimum adverse impact on cost and weight.

5.0 CONCLUDING REMARKS

Table 8 is a summary of the research and development recommended for increased reliability, including an estimation of the impact on size, configuration, and mission applicability. All items considered are listed, even those having a low priority and/or low payoff. Estimated nonrecurring costs and timing are also included in Table 8.

Table 8 gives an assessment of the priority and payoff for each recommended R&D program as well as the applicability to each size helicopter in the civil fleet. As is shown, it is recommended that a high priority should be directed at R&D programs to improve the propulsion subsystem reliability. This subsystem has the largest frequency of problem occurrence, the largest costs of associated repairs, and requires substantial on-aircraft unscheduled maintenance manhours to correct reliability problems. The payoff from propulsion subsystem R&D is expected to be high. Initial studies are directed at detailed problem identification.

The following areas of research defined in Table 8 are of benefit to more than one subsystem:

- Vibration and load reduction are of benefit to the airframe, rotor, and drive subsystem as many of these subsystem problems are known to be related to high vibration levels or unanticipated loads.
- Spline lubrication improvements should alleviate propulsion subsystem problems with fuel splines and drive subsystem problems with drive shaft splines.
- Improvements in filtration will benefit the engine lubrication system and will also give improved seal life in the hydraulic actuators.

Airframe subsystem problems originate from vibration and also from inability to withstand maintenance and operational loads. The requirements of the user's real environment need a better definition. Use of composite structures will alleviate many airframe skin and structure problems, but a development program for compatible hardware is suggested to avoid introduction of new problems.

Drive subsystem materials and lubricant development programs are recommended to improve the overall reliability level of the next generation of helicopters (ref. 1).

Many rotor problems will be alleviated if further development of composite and advanced composites structures results in the widespread use of bearingless main and tail rotor hubs. Corrosion-resistant, easily maintained blades with judicious use of advanced composites will give optimum structural characteristics while keeping the reliability gains associated with the composite blade. At the same time development of design parameters for oscillating seals and lubrication-free bearings such as elastomeric and TEFLON fabric is recommended.

Development of improved coatings for metallic dynamic system components is recommended to protect components from corrosion and maintenance damage.

TABLE 8. RECOMMENDED RELIABILITY IMPROVEMENT R&D PROGRAMS

Research Area/Item	Priority	Applicability	Payoff	Estimated Cost (\$ x 1,000)	Elapsed Time (yr)
Propulsion Subsystem (Turbine Engines)					
Fuel Control/Fuel Governors					
Study of failure modes*	High	All (turbines)	High	100	1
Develop diagnostic fault isolation	High	All	High	300	3
Compressor/Turbine Failure					
Study of failure modes*	High	All	High	100	1
Inlet screen effectiveness study*	High	All	High	50	0.6
High-temp materials, coatings	Low	All	Low	300	3
Engine Lubrication Systems					
Study of failure modes*	Low	All	Low	25	0.4
Improved filtration demonstration	Low	All	Low	25	1
Fuel Pump Splines					
Develop improved spline lubrication	Low	All	Low	100	2
Airframe Subsystem					
Skin and Structure, Small Hardware, and Honeycomb Skin Unbonding					
Study to define maint/operational environment*	Medium	All	Medium	25	0.5
Implement composite structure program of ref. 3	Medium	All	Medium	—	—
Implement vibration reduction program of ref. 2	Medium	All	Medium	—	—
Fastener/hardware development program	Low	All	Low	75	2
*Successive product improvement or research and development program to be defined by this program.					

TABLE 8 -- Continued

Research Area/Item	Priority	Applicability	Payoff	Estimated Cost (\$ x 1,000)	Elapsed Time (yr)
Drive Subsystem					
Transmission Bearings and Gears					
A materials development program for bearings, gears, and housings per ref. 1	Medium	All	Medium	500	3
A lubricants development program for gears and bearings	Medium	All	Medium	150	2
Vibration reduction programs per ref. 2	Medium	All	Low	—	—
Transmission Housing Cracks (main and tail rotor housings)					
Vibration reduction programs per ref. 2	Medium	All	Medium	—	—
Hanger Bearing Failure (can be alleviated by product-improvement-type changes)					
Drive Shaft Splines					
Improved flexible couplings	Medium	All	Low	200	3
Improved lubricants	Medium	All	Low	250	3
Rotor Subsystem					
Blade Cracking, Corrosion					
Advanced composite blade development per ref. 3	Low	All	Low	—	—
Tension-Torsion Assembly Failure					
Support continued bearingless hub development per ref. 15	Medium	All	Medium	—	—

TABLE 8 - Continued

Research Area/Item	Priority	Applicability	Payoff	Estimated Cost (\$ x 1,000)	Elapsed Time (yr)
Rotor Subsystem (continued)					
Hub and Swashplate Support Cracking					
Rotor loads and vibration reduction as outlined in ref. 2	Low	-	Low	-	-
Hub Bearing Failure					
Support continued bearingless rotor development per ref. 15	Medium	All	Medium	-	-
Support continued development of elastomeric and dry-lubricant bearing technology	Medium	All	Medium	400	3
Main Rotor Retention Nut Failure					
Develop redundant hardware for dynamic systems and flight controls similar to civil aircraft applications	Low	All	Low	75	1.5
Tail Rotor Grip Bearing Failure					
Support continued development of elastomeric and dry-lubricant bearing technology	Medium	All	Medium	400	3
Swashplate Support Bearing Failures					
Support continued development of elastomeric and dry-lubricant bearing technology	Medium	All	Medium	400	3
Main Rotor Mast, Hub Corrosion					
Develop improved corrosion-resistant, damage-tolerant coatings	Low	All	Low	100	2
Continue development of the composite bearingless main rotor	Low	All	Low	-	-

TABLE 8 - Continued

Research Area/Item	Priority	Applicability	Payoff	Estimated Cost (\$ x 1,000)	Elapsed Time (yr)
Rotor Subsystem (Continued)					
Rotor Hub Seal Leaks					
Seal development program	Low	All	Low	300	2
Continue elastomeric, dry-lube bearing development	Low	All	Low	400	3
Continue composite bearingless main rotor development	Low	All	Low	-	-
Landing Gear Subsystem					
Float Leaking					
Materials and structure development program	Low	Small/medium	Low	100	2
Hydraulics Subsystem					
Flight Control Actuator Seal Leaking					
Seal/filtration R&D	Medium	All	Medium	100	2
Fuel Subsystem					
Fuel Pressure Switch Failure (can be alleviated by product-improvement-type changes)	-	-	-	-	-
Fuel Pump Failure (can be alleviated by product-improvement-type changes)	-	-	-	-	-
Fuel Cell Leakage					
Development of improved materials	Low	All	Low	200	2

Materials and structures developments in float materials and for fuel cells will improve the damage tolerance without the adverse weight impact now associated with chafe- and puncture-resistant fabric structure.

A final recommended program is for the development of improved actuator seals, as flight control actuator leakage is a generic problem that has been increasing in magnitude as the civil helicopter size has been increasing and the use of power- and stability-assisted flight controls becomes more widespread.

The estimated costs and elapsed time for each R&D program have been given in Table 8. Additional funding will be required for follow-on action after completion of the study programs such as the three propulsion subsystem studies to determine the detailed failure modes and problem causal factors. It is anticipated that the studies will define any additional requirements.

All program costs shown in Table 8 are not additive as several problems call out the same research program as a solution and the entire program cost was repeated for each problem entry. No attempt was made to allocate the costs of a program among the several problems that it would alleviate.

This study has shown that a small number of reliability problems have a major impact on unscheduled maintenance manhours and repair parts cost. The propulsion, drive, and rotor subsystems represent over 80 percent of these manhours and parts cost and additionally have a substantial impact on safety and mission reliability (aborts). Therefore the highest priority efforts must be directed at improving reliability of these subsystems. The airframe subsystem contributes significantly to unreliability because of a large number of failures and maintenance manhours expended.

The research and development identified herein will have a long-term impact on reliability.

The importance of aggressive product-improvement programs using known technology must be emphasized because these will have a more immediate impact on new helicopters now being developed for the civil market.

APPENDIX

CIVIL HELICOPTER RELIABILITY PROBLEMS

Included in this appendix are detailed technical discussions of the individual civil helicopter reliability problems for:

1. The top 20 most frequently reported problems,
2. The top 20 maintenance manhour problems,
3. The top 15 repair parts cost problems.

For convenience an index of the problems is listed by subsystem.

<u>Component/Subsystem</u>	<u>Reference Number</u>
Propulsion Subsystem	
Fuel Control	P1
Fuel Governor	P2
Compressor Failure	P3
Engine Lubrication	P4
Fuel Pump Spline Wear	P5
Turbine Failures	P6
Airframe Subsystem	
Airframe Skin and Structure Cracks	A1
Small Hardware Loss or Failure	A2
Skin Unbonding	A3
Drive Subsystem	
Transmission Bearing Spalling	D1
Tail Rotor Transmission Mount Cracks	D2
Transmission Housing Cracking	D3
Hanger Bearing Failure	D4
Gear Scuffing and Spalling	D5
Drive Shaft Spline Wear	D6
Rotor Subsystem	
Blade Cracks and Corrosion	R1
Tension-Torsion Assembly Failure	R2
Swashplate Support Cracking	R3
Rotor Hub Bearing Failure	R4
Main Rotor Retention	R5
Tail Rotor Grip Bearing Failure	R6
Swashplate Bearing Failure	R7

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CLASSIFICATION

Component/Subsystem Reference Number

Main Rotor Mast Corrosion R8
Rotor Hub Seal Leaks R9
Rotor Hub Corrosion R10

Landing Gear Subsystem

Float Leaks L1

Hydraulic Subsystem

Flight Control Actuator Leaks H1

Fuel Subsystem

Fuel Pressure Switch Problems F1

Fuel Pump Failure F2

Fuel Cell Leakage F3

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CIVIL HELICOPTER RELIABILITY PROBLEM P1

FUEL CONTROL

Problem

The engines widely used in civil helicopters have a gas generator-turbine-compressor unit and a power turbine. The fuel control portion of the fuel system provides the fuel management during engine starting and up to the flight range of the power turbine, approximately 85 to 100 percent of the normal flight rpm. In the upper speed range, the governor controls the speed. Common malfunctions of the fuel control are improper starting and fluctuations of speed in the lower ranges. There is little corrective action possible for fuel controls in the field, so the most common correction of a malfunctioning fuel control is to remove and replace the unit.

Often a unit is removed as part of a troubleshooting operation and subsequent test and disassembly show the unit is fully functional with no defect.

A study of the turbine engine reliability problems of Army helicopters (ref. 8) reports the following failure modes of fuel control units:

- Contamination from the actuating media or from the fuel itself causing sticking and binding of spools, leakage of valves, and clogged orifices.
- Wear on moving or contacting elements.
- Fatigue failure of springs, bellows, and retention devices.
- Misadjustment, erroneous troubleshooting, etc. (estimates of this problem are as high as 50%).

Problem Solution

Present Technology. — The problems are not defined in detail in the civil helicopter data base. The prime engine manufacturer does not usually perform the detailed design, manufacture, or overhaul of the fuel control and seldom has detailed awareness of failure mode and frequency of this assembly. The area needs considerable study to define the problem prior to establishing a solution. Records do indicate substantial differences between failure rates on the fuel controls of different model helicopters, indicating some technology is present for alleviating the problem.

A fleet evaluation program of the comparative reliability of present engine fuel controls with similar units protected by better filtration is recommended. This will document the magnitude of the possible reliability improvement and cost, weight, and complexity penalties of improved filtration.

It is also recommended that a joint airframe/engine/control manufacturer effort determine causes and make recommendations for correcting fuel control problems.

Advanced Technology. — This item is one of the major erroneous-removal problems encountered in turbine helicopters. As many as 65 percent of the military helicopter fuel controls removed in the field exhibit no defect when tested in the shop. This problem appears to be installation/interface-related and is a candidate for additional research prior to complete problem resolution.

A field diagnostic/inspection technique is required so that erroneous removals can be minimized. One option to be considered is the development of a field-level GSE item for off-aircraft fuel control checkout.

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CIVIL HELICOPTER RELIABILITY PROBLEM P2

FUEL GOVERNOR

Problem

The function of the governor is to maintain nearly constant power turbine rpm in response to wide variations in power demand by the pilot's collective setting, while the turbine speed is in the 90- to 100-percent range. Common symptoms of a malfunctioning governor are speed variations, torque and turbine temperature variations, and a drop in rpm occurring with a demand for power. The solution for a malfunctioning governor is to replace the component. Very little on-aircraft maintenance is conducted. Often a governor is removed as part of a troubleshooting operation and subsequent test and disassembly show the unit is fully functional with no defects.

The governor of a twin-turbine engine helicopter has more demanding requirements. The engine torques and turbine inlet temperatures should be matched throughout the flight range, and it is apparent to the pilot if the governor actions result in a variance.

Problem Solution

Present Technology. — As with the fuel control system, the problems are not determinable in detail. The prime engine manufacturer does not perform the detailed design, manufacture, or overhaul of the fuel governor and seldom has a detailed awareness of failure modes. The area needs additional study to define the problem prior to establishing a solution. It is recommended that a joint airframe/engine/governor manufacturer effort determine causes and make recommendations for correcting fuel governor problems.

Advanced Technology. — As with the fuel control, a large percentage of the fuel governor removals has no defect when checked at the factory/overhaul facility. This item requires a field diagnostic/inspection technique so that erroneous removals can be minimized. One option to be considered is the development of a field-level GSE item for off-aircraft fuel governor checkout.

CIVIL HELICOPTER RELIABILITY PROBLEM P3

COMPRESSOR FAILURES

Problem

Civil helicopter-reliability data lists only "failure" as the principle malfunction of the compressor. Virtually every internal engine failure is cause for removal; therefore, to an operator failure description is of little importance. Also, the real failure causes and modes can usually be determined only after disassembly so they are not known to the operator.

A study of many of the same engines used in the civil fleet but installed in Army helicopters (ref. 8) reported the following as the major compressor failure modes:

- Corrosion/erosion-induced vane failures
- Blade/disk fatigue failures
- Diffuser cracking and leakage
- Compressor lining wear and cracking (this was a problem peculiar to one engine design)
- Variable stator and bleed problems (looseness and mechanism failure)

A tabulation of the reasons for military helicopter unscheduled engine removals given in the reference 8 report showed that a total of 41.6 percent of all engines removed was due to compressor problems (compressor failures, FOD, and erosion, with FOD the predominant failure cause).

Problem Solution

Present Technology. — The compressor failures must be examined in more detail to see if the civil helicopter problems are due to detail design execution or require an advancement in technology. The problems may be solvable with existing technology once the details of the failure modes are determined. It is possible that solution requires a means of establishing a cost incentive to justify the corrective action.

If, for example, FOD is the predominant cause of failure, the cost of the present poor reliability and engine repair may outweigh the adverse cost and weight of inlet screens.

It is recommended that a joint airframe/engine manufacturer effort determine causes and make recommendations for correcting compressor problems. To aid in this investigation, it is recommended that the FAA M or D report be revised to request that additional data on failure causes be supplied when this form is submitted by the engine overhaul facility.

Advanced Technology. — Since the civil helicopter data base does not contain depot tear-down/overhaul results, this discussion is based exclusively on military helicopter experience.

The development of erosion-resistant blade vane materials and corrosion-preventive coatings, coupled with the development/application of effective air particle separators, is required to reduce the magnitude of this problem. The GE T700 engine has addressed all of these problems and a study of the effectiveness of R&M improvements on the T700 is being conducted by GE for USAAMRDL. This may identify the areas of additional R&D required.

CIVIL HELICOPTER RELIABILITY PROBLEM P4

ENGINE LUBRICATION SYSTEM MALFUNCTION

Problem

The civil helicopter engine lubrication system component failures and failure modes are not well-defined. Many lubrication system failures jeopardize the engine and so the entire engine with its lubrication pumps, filters, and valves is sent to a distribution center for rework or checkout.

A study of military helicopter engine R&M factors (ref. 8), reporting on many of the same engines used in civil helicopters, gave two major categories of lubrication system malfunctions:

1. Pumps and associated valving
2. Coolers and filters

Tubing and fittings, leakage, and chafing made up the balance of the problem.

Problem Solution

Present Technology. — The problem can be somewhat alleviated by additional filtration to restrict any debris generated from contaminating the entire system and requiring the replacement of both engine and helicopter-mounted components. Failure to remove the entire system has resulted in residual contamination causing secondary failures.

A field evaluation program of the comparative reliability of present engine lubrication systems with similar systems protected by better filtration is recommended. This will document the magnitude of the possible reliability improvement and the cost, weight, and complexity penalties of improved filtration.

It is also recommended that a joint airframe/engine manufacturer effort be made to determine other causes and make recommendations for correcting engine lubrication system problems.

Advanced Technology. — Redundancy of the lubrication system may slightly increase the frequency of malfunction of these components, but the consequence of a failure in terms of safety as well as in unscheduled maintenance manhours and repair parts costs becomes relatively benign.

CIVIL HELICOPTER RELIABILITY PROBLEM P5

FUEL PUMP SPLINE WEAR

Problem

Wear of gas-turbine-driven fuel pump splines has been a significant problem for over a decade. The spline drive is generally lubricated only at assembly and operates at high speed and with some misalignment and lack of concentricity.

The motion of spline surfaces with conditions of marginal lubrication generates wear debris which acts as an abrasive to generate still faster wear rates. In the fuel pump environment, fuel contamination may wash away any grease. The emphasis on low weight results in high spline tooth-contact stresses and further aggravates the problem.

Problem Solving

Present Technology. — The problem can be alleviated with present technology but with an adverse impact on weight and cost. Spline wear is reduced by using a slower-speed drive, keeping contact stresses low in the spline teeth, and minimizing misalignment both by configuration and by closer control of tolerances.

Design changes so that splines of this type can be relubricated without disassembly would give considerable improvement. This is a product-improvement-type change rather than an R&D program.

Advanced Technology. — Design for longer spline life is an area in which R&D will show a payoff and such a program to include materials, configuration, and lubricants is recommended. Considerable work is being done by the military organizations and any additional research should be interfaced with their effort. A recent development of the Naval Air Systems Command, for example, is a polyimide sleeve between male and female spline portions which prevents metal-to-metal contact and accommodates misalignment.

CIVIL HELICOPTER RELIABILITY PROBLEM P6

TURBINE FAILURES

Problem

Civil helicopter reliability data lists "failure" as the principle R&M impacting malfunction of the engine. Virtually every internal engine failure is cause for removal, so to an operator failure description is of little importance.

The real failure causes and modes can usually be determined only after disassembly, so they are not known to the operator.

A study of Army turbine engines made to determine R&M factors (ref. 8) covered many of the same engines used in the civil helicopter fleet. This report gave the following as major turbine failure modes:

- Nozzle band cracking
- Nozzle support structure wear/cracking
- Nozzle erosion, burning, sulfidation

Blade/wheel cracking is an infrequent failure mode. This area is safety-impacting and is given a proportionally larger amount of design attention.

The major R&M problem, then, is caused by thermal stresses, thermal weakening, and the erosive effects of the hot gases.

Problem Solution

Present Technology. — The civil helicopter turbine failure data base should be expanded to allow examination in greater detail. While some problems appear to be alleviated by existing design techniques, the inevitable use of higher turbine pressure ratios and operating temperatures and the trend to increase power-to-weight ratios make this an area for continued research. A joint airframe/engine manufacturer effort is recommended to determine causes and resolution of turbine reliability problems.

Advanced Technology. — Since the civil helicopter data base does not contain depot teardown/overhaul results, this discussion is based exclusively on military helicopter experience.

The use of cast nozzles and slotted inner/outer nozzle bands, along with the development and application of improved materials, directional solidified alloys, and improved coatings to resist sulfidation, would be a great step toward reducing the magnitude of this problem. Analogously, development/application of turbine engine fuels with lower sulphur content would have a highly beneficial effect upon turbine reliability. A materials/coatings development program is recommended to alleviate future turbine area problems.

CIVIL HELICOPTER RELIABILITY PROBLEM A1

AIRFRAME VIBRATION AND CRACKING

Problem

Airframe skin and structure cracks result from three major factors:

1. High localized vibration (particularly in the vicinity of the rotors and engine) and pulsating airloads due to rotor downwash on top surfaces.
2. Load concentration typically in the areas of:
 - Door attachments
 - Landing gear attachments
 - Tailboom attachments
 - Engine attachments
3. Maintenance-originated damage primarily in the areas of:
 - Doors, access panels loaded abnormally (wind load on open panel; vertical loads on open doors; doors opened too far, thus cracking structure at hinges; bent structure which results in cracking due to load concentration in operation)
 - Stringers and longerons dented from maintenance, which then crack due to load concentrations
 - Damage from tools and toolboxes resting on horizontal surfaces which are primarily fairings
 - Denting, damage from stepping on nonwalkway areas
 - Cargo, passenger-loading damage of unreinforced areas

Problem Solution

Present Technology. — The problem can be greatly alleviated with existing technology but with a weight penalty. The design approach is twofold:

1. Design for the real maintenance and user environment, that is:
 - Heavier skin on horizontal surfaces
 - Better work platforms
 - Components designed to be resistant to maintenance damage. Avoid flimsy edges on formers and stringers that may be exposed to maintenance damage.
2. Design for higher load factors, that is:
 - Reinforce structure at points of load transfer

- Design to be more resistant to vibration in areas demonstrated to be vulnerable to this source of problems

Advanced Technology. — The following areas of technology offer considerable promise:

1. Advanced materials, which promise weight reductions of 12 percent with present design principles, offer a means of design to the real maintenance and vibration environment with equivalent weight as compared to today's technology (ref. 3).
2. Reduction of the vibration levels. One method is to use isolation systems between the fuselage and the rotor system. The airframe will then be less susceptible to vibration-induced cracks (ref. 2).

Additional References. — A further discussion of the skin and structure cracking problem of two military helicopters is given in reference 10. An excellent summary of the effects of maintenance/operational damage on the U.S. civil helicopter airframe is given in reference 16.

CIVIL HELICOPTER RELIABILITY PROBLEM A2

SMALL HARDWARE

Problem

Hinges, latches, rivets, screws, and other hardware fail at such a rate as to cause a significant R&M problem. The problem is usually minor per event, but the frequency of occurrence is very high. One study of military helicopters (ref. 10) reported that hardware problems accounted for 15 percent of the total malfunctions on two models of helicopter. There is some safety implication as panel loss resulting in rotor contact has occurred. FOD to engines from lost hardware is another safety hazard. The causal factors of noncombat military helicopter hardware failures have been studied by several investigators (ref. 10, 13, 17, 18). Major causes from reference 13 are given below. An examination of civil helicopter hardware failure data indicates the same causal factors are occurring. The causes are:

- Vibration-induced failures caused by loads imposed by adjacent structure
- Maintenance damage caused by excessive loads applied while securing the fastener or by rough handling of hardware or attached structure
- Manufacturing-tolerance variations that cannot be accommodated without damage to the fastener

The civil helicopter problem is nicely summed up in a recent statement by Frank McGuire, Editor, Helicopter News (ref. 16): "In many ways the helicopter is just out and out too flimsy."

Problem Solution

Present Technology. — The frequency and severity of the small hardware problem can be greatly alleviated with present technology once it is acknowledged that there is a requirement for a rugged design to survive in the user's environment; that is, design for the following:

- Resistance to vibration
- Tolerance to maintenance damage
- Crew, passenger, baggage, and cargo-damage tolerance

A program for field evaluation of the reliability of an airframe reinforced locally to withstand high vibration levels, normal maintenance and operational loads, and with the hardware installation inspected to assure all aspects are according to manufacturer's requirements. This will enable a quantitative determination of the reliability improvement and associated weight/cost penalties available with the present small hardware technology.

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Advanced Technology. —

- More study and definition of the operational design criteria will permit a weight- and cost-effective approach for hardware survival.
- Fastener research is required to improve the tolerance to maintenance and manufacturing discrepancies.
- Hardware must be developed to be more compatible with the use of composite and honeycomb construction. Present hardware is based on decades of use with solid metal structure and some proves inadequate when used with composite or honeycomb.
- Vibration levels should be reduced. One method would be to develop and field-test a vibration-isolation system.

CIVIL HELICOPTER RELIABILITY PROBLEM A3

SKIN UNBONDING

Problem

Civil helicopters make wide use of honeycomb panels; they are highly efficient from a strength-to-weight ratio. Both metal and composites are used for skin and core, although use of metal is more prevalent. Unbonding of the skin and core is a widely experienced problem.

Honeycomb panels are frequently built into the primary aircraft structure and replacement is a major operation. Repair of a large unbonded area is also difficult and time-consuming.

There are many reasons which have been found for this problem which is most predominant with the metal honeycomb construction:

1. Manufacturing/processing methods have been at fault. Proper cleaning and surface preparation of materials have been found essential to good performance.
2. Some hygroscopic bonding materials have been used; these transmit moisture which corrodes the metallic surfaces and causes the bond failure.
3. Attachments, such as fasteners and other hardware, are not sealed which results in moisture and fluid penetration.
4. Mechanical damage, such as punctures, allows moisture and other fluids to enter the honeycomb core. Aluminum skin on the order of 0.010 inch thick is often used which is structurally adequate, but nearly intolerant of maintenance, crew, or cargo damage.

Many panels now in use in the civil helicopter fleet, although quite new in chronological age, represent somewhat obsolete design and fabrication techniques because of the rapid changes made in this area of structures technology.

Problem Solution

Present Technology. -

- Considerable research has been done in the areas of improved processing and bonding agents, so the problem will be alleviated as these procedures are implemented.
- Use of composites has resulted in fewer bonding problems than the metal honeycomb structure.
- Better fastening methods to the honeycomb panel have been developed so that better sealing results against external moisture and fluid contamination.

-A field demonstration program could evaluate the reliability improvement possible for a historically troublesome honeycomb panel installation if the current technology in composite

materials, manufacturing and process controls, and panel design configuration were combined to make a replacement panel. The field reliability problems experienced by this present-technology panel would enable a cost-weight-reliability trade to determine the effectiveness of fleet retrofit of present technology to replace that now in use in the civil helicopter fleet.

Advanced Technology. — Work is needed in the following areas:

- Better definition of the requirements of the operational environment is needed, particularly in the areas of maintenance, crew, and cargo-damage potential.
- Better definition (supported by testing) of the damage-tolerant performance of honeycomb skins of different thicknesses and materials.
- Better fastener and attachment procedures and hardware are required to assure fewer load-transfer discontinuities at these points. Design criteria should be better defined; for example, a desirable feature would be to require fastener attachments to exceed the strength of the attached hardware, so that any maintenance damage results in failure of the low-cost fastener, rather than the high-cost panel. This is particularly necessary for composite panels since there is a lack of technology in this area.

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CIVIL HELICOPTER RELIABILITY PROBLEM D1

TRANSMISSION BEARING SPALLING

Problem

Spalling (or flaking) of bearings is the result of fatigue failure of the contacting surfaces. If the bearing is properly made, mounted, and lubricated and the loads are not excessive, bearing spalling should occur only infrequently.

Common problems found to contribute to transmission bearing spalling are the following:

1. Unanticipated loads, in excess of the design load spectrum.
2. Lack of cleanliness of the bearing material. Inclusions or flaws act as origins for incipient failure.
3. Misalignment or other assembly conditions such as to cause an unanticipated distribution of load.
4. Improper surface finish of the ball, roller, or raceway paths such that lubrication breakdown occurs.
5. Contamination of the lubricant.

In the civil helicopter data base, this problem is associated predominantly with the spalling of the upper shaft support bearing in one model of helicopter and, as such, is not a generic problem to the civil helicopter of the magnitude indicated but rather a particular problem in design execution. Although the magnitude of this problem may be biased by this one specific bearing, as previously shown in Table 3, bearing spalls are the cause of more than 19 percent of all military helicopter transmission unscheduled removals.

Problem Solution

Present Technology. - The particular problem in the one helicopter model that drove this failure cause to the predominant problem list appears to be a matter of design execution. Correction is probably impaired by cost and weight changes and the necessity to change interfacing components.

The generic problem of transmission drive system bearing spalling can be alleviated within the bounds of present bearing technology. Incorporation of the following product-improvement-type design approaches will reduce the problem magnitude:

1. Bearings of VIM-VAR processed steel (M50 or 9310, vacuum-induction-melted or vacuum-arc-remelted) with the forged billet ultrasonically inspected. This material gives fewer and smaller inclusions for possible fatigue failure initiation than single vacuum-arc-melted steels with conventional inspection techniques.

2. Improved quality assurance of critical bearing characteristics such as surface finish and internal clearances, assuring better lubrication and more predictable load-carrying ability.
3. Since spalling is a load-sensitive characteristic, increasing the size of the bearing will reduce the surface contact stresses. The bearing life increases as the inverse of the 7th or 9th power of the contact stress ratios if all other factors remain unchanged. This approach does carry a weight penalty but, since total weight of transmission bearings is only 7 percent of the transmission assembly weight (ref. 1, Figure 18), a trade of this sort (weight increase to increase reliability) may be in order. The problem could then be seen in proper perspective.

Advanced Technology.—The following approaches may further reduce the transmission bearing spalling problem:

1. The civil helicopter fleet has more freedom to use lubricants more suited to the specific application than does the military, which relies on a universal lubricant, suitable for all applications and environments (but possibly optimum for none). Research shows that for many helicopter applications, straight mineral oil gives about twice the life of the military lubricants. One concern is that introducing more lubricant types could create additional logistics (supply) problems.
2. Continued materials research to develop stiffer transmission housings and bearing materials with better load-carrying characteristics. A program outlined in reference 1 is recommended.
3. Vibration reduction to reduce unanticipated loads upon the bearings. The program outlined in reference 2 is recommended.

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CIVIL HELICOPTER RELIABILITY PROBLEM D2

TAIL ROTOR TRANSMISSION MOUNTING

Problem

The tail rotor gearbox mount failures are reported as a problem. The details of the failure are not reported; however, the failures are principally a problem in one model helicopter. This is evidence that this is not a problem indigenous to the civil helicopter, but rather a problem of design execution on the one model that is the principle source of these reported failures.

Failures in the tail rotor area of helicopters are not unusual due to the high vibration and difficulty of accurately predicting loads.

Problem Solution

Present Technology. — Better detailed design execution would reduce the magnitude of this problem greatly. Reliability warranties might increase the cost-effectiveness of design changes to correct this type of problem.

Advanced Technology. — A vibration reduction program, oriented to the tail rotor area, would reduce the frequency of this type of failure which occurs primarily due to unanticipated loads. This program should address the vibration reduction approaches of reference 2.

CIVIL HELICOPTER RELIABILITY PROBLEM D3

TRANSMISSION HOUSING CRACKS

Problem

Cracks in the attachment/lift lugs of the transmission of one helicopter model caused this problem to make the top problem list. The problem is believed to be one of design execution as other helicopters have a much lower frequency of malfunction in this area. The transmission attachment lift lug arrangement in question is designed to isolate the fuselage from rotor-induced vibration. There are six transmission-to-fuselage attachments. One lift link is attached to the forward edge of the transmission and transmits vertical forces with no lost motion; the other five lugs attach to mounts having a degree of resilience. The two aft outboard attachments have friction dampers as well.

Problem Solution

Present Technology. — The particular problem of the helicopter in question appears solvable with present technology with probable adverse impact on cost and weight. The lug attachment cracking problem does not appear to be generic to the civil helicopter.

Advanced Technology. — Reduction of rotor loads and vibration should alleviate this and other unanticipated helicopter component cracking problems. Research requirements for such a program are outlined in reference 2.

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CIVIL HELICOPTER RELIABILITY PROBLEM D4

HANGER BEARING FAILURE

Problem

The drive shafting between the main rotor transmission and the tail rotor transmission is supported by a number of hanger bearings. The shaft weight is generally negligible in terms of the bearing allowable loads, so the principle loads are those caused by structural deflections and vibration. The calculated lives of these bearings are so high that the bearing should not constitute a problem. Yet, the problem of providing axial and angular freedom for shaft deflection makes this a difficult bearing application and the frequency of failure drove this problem to the major reliability problem list.

Problem Solution

Present Technology. — This problem is reported to be more prevalent in one model of helicopter than in the overall civil fleet, leading to the conclusion that the problem is one of design execution and not a generic problem.

In reviewing the history of shaft hanger bearings, it was found that many design approaches have been taken to alleviate this problem with considerable success. These include splined shaft sections to allow axial and angular freedom, flexible couplings between shaft sections, flexibly mounted hanger assemblies, damped hanger assemblies, elastomeric mounting of the bearing, and the requirement for periodic lubrication of the bearing. In general, the more complex and expensive approaches have resulted in more reliable assemblies.

Advanced Technology. — There is a need to determine the life-cycle cost impact of higher initial investment to alleviate this R&M problem.

CIVIL HELICOPTER RELIABILITY PROBLEM D5

GEAR SCUFFING/SPALLING

Problem

Scuffing and spalling of gear teeth are surface distress phenomena. Scuffing is a very localized surface welding and tearing loose caused by sliding of contacting surfaces. Scuffing is an indication of lubrication breakdown at the tooth contact point and an important cause has been found to be improper surface finish. Scuffing is generally initiated during run-in of a transmission and exhibits a decreasing failure rate with time. Spalling results from high contact stresses and is a surface fatigue condition. Spalling generates small metallic particles which are detectable by debris-detection systems. Gear spalling is potentially a nucleus for a more serious tooth fatigue failure but is not safety-critical by itself. Debris generated by spalling and detected by a debris-detection system would be cause for transmission removal and so severely impacts the maintenance cost of a helicopter.

Problem Solution

Present Technology. -- Some of the spalling and scuffing problem can be alleviated by improved control of quality factors as discussed under transmission bearings. This includes:

1. Improved material cleanliness by use of double-vacuum-melt steels with ultrasonic inspection of the billet.
2. Improved surface finish of the contacting areas.
3. Better distribution of lubricant on the contacting surface.
4. A weight/reliability trade to reduce the load-related failure phenomena.

Advanced Technology. -- The following areas of potential R&M improvement in the area of scuffing and/or spalling were identified in reference 1:

1. Improved load sharing and reduced sliding of noninvolute, high-contact-ratio spur-gear teeth provide reduced noise and vibration levels and increased load capacity and life for planetary systems.
2. Increased contact area, reduced misalignment sensitivity, and sliding of nonoctoid, high-contact-ratio bevel teeth provide reduced noise and vibration levels and increased load capacity and life.
3. Advanced hot-hardness gear materials provide increased load capacity and life and increased tolerance to emergency oil-off operation.

4. Advanced finite-element analysis of planetary (spur and helical) and spiral-bevel-gear rim thickness will preclude a catastrophic failure through the gear rim or web and an improved load distribution can be obtained.

In addition to these, improvements in lubricants for gearing offer both short- and long-term possibilities to increase load capacity.

CIVIL HELICOPTER RELIABILITY PROBLEM D6

DRIVE SHAFT SPLINE WEAR

Problem

This problem relates to wear of a spherical-spline used in each of the two flexible couplings of the drive shafting from the engine to the main transmission. The splines accommodate axial motion and misalignment. They are packed at assembly with an extreme-pressure grease. The assembly is sealed.

The problem is associated with the design selection of a soft-mounted rotor transmission system and an airframe-mounted engine. This requires couplings to accommodate large axial motions and angular misalignment. Sealing to retain the lubricant and exclude contaminants is difficult. Seal failure results in lubricant loss and subsequent spline wear.

Maintenance of the drive shaft splined couplings is time-consuming as the shafting must be removed from the helicopter, the couplings disassembled and then inspected for wear, re-grease-packed, and then reassembled.

There is some indication of lubrication breakdown in high-ambient-temperature operation of this drive shaft spline in military helicopters.

Problem Solution

Present Technology. — The flexible coupling configuration which employs a spherical spline was forced by the design configuration of the flexibly mounted transmission with the engine separately mounted on the airframe. With this configuration, the most promising area of present technology is the development of a grease lubrication system that does not require removal from the helicopter and subsequent disassembly. With more frequent lubrication of the splines, the spline wear problem would be alleviated and the R&M impact improved.

Advanced Technology. — Development of improved flexible couplings would improve the helicopter R&M. There is increasing need for shafting to accommodate relative motion between components as rotor-isolation systems are used to reduce the helicopter vibration levels.

Further research on high-pressure spline lubricants, particularly for operation in high ambient temperatures, may also alleviate this problem. Use of dry-lubricant coatings should be considered in any spline lubricant program.

CIVIL HELICOPTER RELIABILITY PROBLEM R1

METAL BLADE CRACKING AND CORROSION

Problem

The metal blades consist of an aluminum extruded spar with an aluminum sheetmetal fairing bonded to the trailing edge. Common failure modes are cracking (predominantly in the bond areas) and corrosion. These are not safety-of-flight problems but must be corrected before they progress to that stage. This blade concept, while initially inexpensive, is very difficult to repair and so a large proportion of damaged blades are scrapped. The blade is susceptible to FOD. Repair of dents makes the blade susceptible to further cracking of the dented area, resulting in subsequent scrapping.

Problem Solution

Present Technology. — The fiberglass composite blade is much less susceptible to bonding cracks, denting, FOD, or corrosion. Although the initial cost of this blade is presently high, with increased production quantities the initial costs are projected to be similar to metal blades. Repair has been simple and inexpensive, resulting in low life-cycle costs.

Advanced Technology. — The use of advanced composites gives better weight-to-strength ratios with R&M characteristics similar to fiberglass and offers overall helicopter performance gains. Thus, the value of advanced composite material application to blades will be in the area of providing R&M characteristics comparable to fiberglass, while simultaneously providing a weight/performance improvement which can be applied for reliability improvement elsewhere in the helicopter. A program is recommended to develop such an advanced composite blade.

CIVIL HELICOPTER RELIABILITY PROBLEM R2

TENSION-TORSION ASSEMBLY FAILURES

Problem

The tension-torsion assembly retains the blade against centrifugal forces while permitting the torsional movement required for blade control. Catastrophic blade loss has resulted from wirepack tension-torsion assembly failures in current turbine helicopters. As the function of the pack assembly is critical to safe operation and any pack deterioration cannot be observed in the aircraft installation, the packs are replaced when any deterioration is found at overhaul, regardless of how serious.

Two forms of deterioration have been observed:

1. The polyurethane cover deteriorates from hydraulic oil or other fluid contamination. This becomes evident from the blistered appearance. (Cover deterioration is a possible cause of pack failure.)
2. Broken wires protrude through the cover.

Although the pack consists of multiple wire windings, the assembly shows little sign of redundancy and acts as a single load path for blade retention.

Problem Solution

Present Technology. — It is probable that continued effort will soon result in complete understanding of problem causal factors and solutions of the wirepack problems. Other approaches for the blade retention problem which have been successfully used are the following:

1. A series of angular-contact ball bearings sharing the centrifugal load as a thrust load on each bearing.
2. Many parallel stainless-steel straps carrying the centrifugal load as a shared tension load and twisting to provide blade pitch freedom.
3. Many parallel metal bars carrying the centrifugal load as a shared tension load and twisting to provide blade pitch freedom.
4. Elastomeric bearings in compression.

These approaches are in use, and as far as is known, none has resulted in a safety-of-flight problem. Some offer positive redundancy in load path and better inspectability of condition. Some require a configuration change to the rotor head. Weight and cost may be slightly affected adversely.

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CIVIL HELICOPTER RELIABILITY PROBLEM R3

HUB AND SWASHPLATE SUPPORT CRACKING

Problem

The problem refers to cracks in dynamically loaded components of the rotor hub and upper controls. The cracks appear repetitively in a few of many similar components and occur as a significant problem in only a few models of helicopters. These components have very little redundancy, and since they are critical to safe flight, they are carefully inspected at frequent intervals once a problem of this type materializes. This adds to the R&M burden.

Problem Solution

Present Technology. - Although the exact causes of this problem are not understood, many similar components are functioning satisfactorily in the same design of helicopters, and many other helicopter designs have components that accomplish the same function as the components in question and are not an R&M and safety problem. This appears to be a problem in detail design execution that may be difficult to correct without a serious impact on cost and weight, and the redesign of the malfunctioning and interfacing components.

Advanced Technology. - The vibration and loads reduction program identified in reference 2, if adapted, will result in better identification of loads. Unanticipated load levels must be a significant factor in this problem.

CIVIL HELICOPTER RELIABILITY PROBLEM R4

HUB BEARINGS

Problem

This problem is the malfunction of rolling-element bearings in the main rotor hub. There are both oil- and grease-lubricated bearings reflected in this problem. The loads have both steady and alternating components and the bearings oscillate through small angular excursions at rotor frequency. Proper functioning of these bearings is essential to minimizing helicopter vibrations. A malfunction, if undetected, can progress to a safety-of-flight problem.

The bearings included are the following:

1. Pitch-change bearings
2. Teetering-hinge bearings
3. Pitch-link-attachment-trunnion-assemblies

Replacement of the pitch-change and teetering-hinge bearings generally requires removal and partial disassembly of the rotor hub, after which a check track and balance should be conducted. Replacement of the pitch link attachment trunnion can usually be done without impact on blade track; however, the check track is desirable. The R&M and cost impact results from the above operations.

Problem Solution

Present Technology. — The problem is most severe on the smallest, more lightly loaded bearing, the grease-lubricated pitch link attachment trunnion bearing. These particular problems could be alleviated by larger bearings, but with some adverse impact on cost and weight.

Advanced Technology. — The bearingless main rotor, with flexing elements rather than rolling-element bearings, is a concept that offers R&M savings. Other promising areas for which technology must be developed to assure a favorable R&M impact are:

1. Elastomeric bearings
2. TEFLON fabric bearings

As discussed in Civil Helicopter Reliability Problem R6 (Tail Rotor Grip Bearings), the technology of design for these bearings under alternating loads and oscillating motion is not currently well enough defined to permit accurate life prediction.

CIVIL HELICOPTER RELIABILITY PROBLEM R5

MAIN ROTOR RETENTION NUT FAILURE

Problem

This problem relates to malfunction and failure of essentially standard hardware and the maintenance impact of such a failure. The failures involved are mainly cracking of nuts on blade retention bolts. Malfunctions involve failure of the nut retaining latch and loosening of the nut. As the nuts in question perform a critical function and have little redundancy, there are safety-of-flight implications from this problem.

The failure causal factors were not reported in the data reviewed. While there are many possible causes for these failures, high-strength aircraft hardware has been found particularly sensitive to materials defects and deviations in manufacturing and processing. Brittle failures of aircraft nuts have been found to have resulted from deviations in the heat-treatment processes.

Problem Solution

Present Technology. — Redesign to use material less sensitive to processing flaws would alleviate the problem, but with an adverse impact on component weight and a redesign and requalification required.

Use of hardware calling for more stringent control of critical processing characteristics would alleviate the problem.

Advanced Technology. — Redundant means of attachment of safety-critical hardware, if developed, would reduce the criticality of this hardware and permit the use of lower heat-treat material, less sensitive to material and processing flaws.

CIVIL HELICOPTER RELIABILITY PROBLEM R6

TAIL ROTOR GRIP BEARINGS

Problem

TEFLON fabric-lined bearings are commonly used for tail rotor blade mountings to provide retention against centrifugal force while allowing pitch freedom, and also as teetering-axis bearings. These bearings are compact and light in weight. They do not need lubrication and generally give excellent, maintenance-free service for a reasonable life. In some applications, however, poor bearing performance results for no apparent reason. Two examples of this are the malfunction of teetering-axis bearings of one helicopter model and the tail rotor bearings of another model.

Replacement of tail rotor bearings is usually followed by a check track and balance; this represents an undesirable burden on maintenance personnel.

The problem is caused by a lack of design criteria for nonlubricated bearings. Very little research has been conducted as to the required load levels and motions which will give satisfactory lives throughout the helicopter dynamic system. Changes in bearing methods of construction and bonding resins which improve performance under one condition are sometimes found detrimental to satisfactory operation under another condition. Most TEFLON fabric bearing testing has been directed at verification of performance for specific applications.

Problem Solution

Present Technology. — The R&M problems of the specific helicopters could be greatly alleviated by a change in component geometry to reduce the loads. This would involve the costs of nearly complete rotor hub redesign and requalification, with probable adverse impact on component procurement costs and weight.

Bearingless tail rotors using flexing elements of fiberglass-reinforced composite have demonstrated excellent performance in two recent helicopter designs. These hubs eliminate all but the pitch-change linkage bearings. This concept should greatly alleviate R&M problems of tail rotor assemblies. This is a product-improvement-type change.

Advanced Technology. — Research is needed to determine the parametric relation of factors influencing TEFLON fabric-lined and other nonlubricated bearing wear.

Elastomeric bearings have the potential for maintenance-free operation for many rotor system applications. Again, considerable research is needed to fully understand the load/motion requirements to give long life in the many differing helicopter dynamic system applications.

CIVIL HELICOPTER RELIABILITY PROBLEM R7

SWASHPLATE BEARING FAILURES

Problem

The many bearings and bushings in the swashplate and support system deteriorate. These are mostly dry-lubricant (TEFLON fabric) bearings, although rolling-element bearings are also involved.

The reported problems involve malfunction of the following components:

- Bearings, bushings, and bolts for swashplate centering
- Uniball for swashplate centering
- Collective yoke bearing
- Swashplate bearing (rolling-element) spalling

In addition to the above, the military version of one model of these helicopters reports a very high deterioration rate of the TEFLON fabric sleeve bearings for swashplate centering.

The problem appears to be associated with the large number of bearings in an installation and the necessity to remove blades, hub, and rotor controls to replace a malfunctioning bearing. Also, deterioration of bearings in the rotor controls results in unacceptable vibration levels so that maintenance cannot be deferred.

Problem Solution

Present Technology. — This is a problem in design execution. The rotor controls are very compact for light weight and low drag. It is difficult to increase the capacity of any one of the bearings once the configuration has been established without impacting the size of the entire assembly. Thus, improving the R&M requires a weight-cost trade, but can be achieved with existing technology.

Advanced Technology. — A new concept of using scissors-type linkages for swashplate centering was developed by Boeing Vertol and used on the YUH-61A and the HLH rotor controls. This linkage was completely replaceable without removing the rotor system and thus, the R&M impact of bearing replacement is minimized.

Further development of the technology of TEFLON fabric and other dry-lubricant bearings, as well as elastomeric bearings, would aid in life prediction of future bearings of this type and so reduce the magnitude of this problem in future helicopters.

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CIVIL HELICOPTER RELIABILITY PROBLEM R8

MAIN ROTOR MAST CORROSION

Problem

The definition of the specific areas of corrosion was not given in the data reviewed. It is not clear whether the problem is in either of the splined areas, the threaded areas, or inside or outside the main transmission.

The main rotor mast is a dynamic component whose integrity is critical to flight safety, and the permissible damage level from nicks, dents, or corrosion is low. The corrosive damage permissible on one area of the rotor shaft of a military version of one of the more widely used civil helicopters is limited to that amount that can be cleaned up with steel wool.

Problem Solution

Present Technology. — The technology exists to improve the corrosion resistance of each of the areas of the rotor mast, either by damage-tolerant coatings over the plated exterior surfaces, additional seals, shields, and boots to protect unplated surfaces and threads, and corrosive-resistant oil-compatible coatings for the shafting inside the transmission. Redesign, additional procurement cost, and possible complexity become the trade for alleviating the R&M impact. The problem also could be alleviated by a redesign to reduce the criticality of corrosive damage. This would adversely affect weight.

Advanced Technology. — Development of improved corrosive-resistant, damage-tolerant coatings would alleviate much of the helicopter R&M cost problem.

CIVIL HELICOPTER RELIABILITY PROBLEM R9

ROTOR HUB LEAKS

Problem

Although not a high-failure-rate item, leaking of oscillating seals in the rotor hub is a traditional helicopter problem. These seals retain the oil for the main rotor hinge-bearing lubrication. The problem is that the usage of the seals is small and so it has never been profitable for a seal manufacturer to develop the technology for this nearly unique application. Helicopter manufacturers have conducted thousands of hours of seal testing aimed at development of a successful seal for a specific application, rather than development of parameters necessary to insure a successful seal. The R&M impact of a seal failure is severe as it is necessary to remove the blades and hub to replace the seal, then reassemble and retrack the blades.

Problem Solution

Present Technology. — The random nature of the seal leakage problem indicates a deviation in materials or manufacturing process control. Increased quality assurance that seal components are meeting specified design requirements and that critical processes are properly controlled are the most effective areas of present technology to alleviate this R&M problem.

Advanced Technology. — The following areas of further research should be examined:

- A program to determine design parameters for oscillating seals.
- A program to evaluate flexible boot-type seals.
- Development of elastomeric or other sealless bearings.
- Development of bearingless rotor hubs.

CIVIL HELICOPTER RELIABILITY PROBLEM R10

ROTOR HUB CORROSION

Problem

The cadmium-plated steel and the aluminum surfaces of rotor hub components corrode when the surface finish is scratched, worn, or otherwise damaged. As the major hub components are dynamically loaded and have little redundancy, corrosive damage in a critical area in excess of 0.005 inch in depth is sufficient to cause the component to be rejected. Many areas cannot be properly inspected or repaired on the aircraft. Consequently, if damage is suspected in these areas, the rotor blades and hub must be removed from the aircraft. This causes the R&M impact.

Problem Solution

Present Technology. — As the damage is maintenance-initiated for the most part, a tougher surface coating such as a polyurethane base would alleviate the problem, although impacting adversely the procurement cost of components. The life-cycle cost would be reduced, however, by the reduced maintenance requirements.

Other corrosion-resistant materials (titanium and stainless steels) and coatings (nylon powder and plasma spray) will reduce R&M problems with present design configurations.

Advanced Technology. — The composite rotor hub (bearingless main rotor) as discussed in reference 14 offers corrosion resistance as well as weight savings.

CIVIL HELICOPTER RELIABILITY PROBLEM L1

FLOAT LEAKS

Problem

Leaks in floats can be a serious safety-impacting problem because, in some operations, floats are used only in emergency landings. Two types of float are involved: the permanent installation and the emergency type. The latter float is carried collapsed and is inflated for emergency water landing. Reported failures are as follows:

1. Permanent floats – Abrasion and chafing, both from landing and from passengers/crew entering and leaving the aircraft, cause leaks.
2. Collapsible floats – Primarily, these leak at pinholes and seams; occasionally they are found to have chafing damage. Chafing occurs in the packaged float when aircraft deflections result in relative motion between adjacent layers of fabrics. The floats must be tested at regular intervals. They fail to inflate and are found to leak.

Float materials are deteriorated by sunlight and contamination such as is caused by petroleum-based fluids and other common chemicals such as cleaners. Abrasion is caused by sand, dirt, and mechanical damage. The floats can be easily punctured. Both over- and under-inflation can be structurally damaging, yet the normal operating pressure range is only from 1.5 to 2.0 PSIG. (A 30-degree increase in temperature will cause approximately 1 PSIG change in pressure, as will a 2,000-foot altitude change at standard atmospheric conditions.)

Floats are designed to meet critical target weights and must be treated with consideration for the inherent material characteristics if trouble-free service is desired.

As explained in the Landing Gear Subsystem Discussion, Section 3.2.5, the float reliability problem was greatly alleviated when one of the major float manufacturers instituted an aggressive product-improvement program in 1974. Following this a dramatic reduction in float failure rate became evident; with this lower rate float leaks would no longer be ranked as a major problem. It is interesting that part of the reliability improvement came from the use of heavier fabric coatings and additional fabric chafing strips.

Problem Solution

Present Technology. – Float reliability can be improved by the judicious addition of weight. Heavier materials and more reinforcement of materials are examples of this approach. Float procurement specifications should require abuse resistance more typical of the real operating environment and permit increased weight to achieve this reliability.

Advanced Technology. – This problem appears unique to civil helicopter operation. Military helicopter operation with floats is quite limited so little research is done by the military organizations.

Research to develop new materials and new construction methods is needed so that the adverse weight impact of a reliability improvement can be minimized.

Development of weight-cost-reliability trade criteria would assist in the selection of an optimum design float for the desired application.

CIVIL HELICOPTER RELIABILITY PROBLEM H1

ACTUATOR LEAKS

Problem

Flight control actuator seal leakage has been a recurring problem in helicopters ever since hydraulic boost systems have been employed.

The flight control actuator reacts rotor control forces. These forces alternate, coming to a peak each time a blade passes over the fuselage. As the hydraulic cylinder acts as a stiff spring, the piston moves in the cylinder N times per rotor revolution, where N is the number of blades. This motion wears seals. The pressure pulses generated deform the seal at the same frequency, generating further wear. Since any generated metallic wear debris is abrasive, it results in accelerated wear. External contamination of the fluid or seal causes further acceleration of wear.

Improvements in seal technology have alleviated these problems by research in the following areas:

- Improved seal configurations
- Improved piston, piston rod, and cylinder materials and coatings
- Improvement in filtration of the hydraulic fluid
- Boots and scraper rings to exclude contaminants
- Multiple vented and unvented seal concepts

Actuator sizing is another factor in seal wear. A large actuator is stiffer hydraulically than a small one, so that less motion results from the alternating loads. The reduced motion improves the seal life.

The generic problem of actuator leakage in civil helicopters does not appear to be as much of a problem as indicated by the data. This is because the leakage in one model of helicopter drove this problem to the major R&M problem list.

Problem Solution

Present Technology. — The severe seal leakage of the one model helicopter mentioned previously appears to be the result of design execution. It would appear that the problem could be reduced to the acceptable level of other helicopters by using existing technology, although with a possible adverse impact on initial cost and weight.

Advanced Technology. — The entire area of sealing and filtration is a subject that deserves further research in order to improve the R&M factors of future civil helicopters.

CIVIL HELICOPTER RELIABILITY PROBLEM F1

FUEL PRESSURE SWITCH

Problem

Fuel pressure switches are commonly used to signify loss of fuel boost pressure. The electrical signal goes to a caution light. Some helicopters have another pressure switch to signal that the fuel filter is blocked and is about to bypass. The switch is usually a sealed assembly that is replaced rather than repaired. Consequently, failure modes are not defined. Some of the problems reported are:

- A susceptibility to fuel contamination
- Maintenance damage
- Deterioration from the vibratory environment (this is especially predominant in unpotted switches)

Problem Solution

Present Technology. — A better definition of failure modes is required and the modes must be associated with design approaches.

Some pressure switches have been examined that have good, sturdy construction, with wrench flats to avoid maintenance damage. Others have been examined that have a highly cantilevered support, so that they are susceptible to vibratory or maintenance damage, have no wrench flats so that vise grips or pliers must be used for installation and removal, and the electrical assembly is susceptible to overtorque. Surprisingly, the latter switch carries a weight penalty in addition to other disadvantages.

These factors indicate that product-improvement-type changes will greatly alleviate this problem.

Advanced Technology. — It is probable that no new technology is required but merely a careful definition of requirements to survive in the real environment. This will then require an investment to design and fabricate components to meet these more demanding specifications.

CIVIL HELICOPTER RELIABILITY PROBLEM F2

FUEL PUMP FAILURE

Problem

The civil helicopter normally has fuel boost pumps to pump from the fuel tank to the engine and an engine-mounted pump to maintain controlled pressure to the fuel nozzles. Malfunction of both of these pumps has been a historical problem in the civil helicopter fleet. The fuel boost pump is technically considered part of the fuel system, while the engine-mounted pump is technically a powerplant component. While the problem is reported as that of a fuel-system-pump failure (i.e., the fuel-boost pump), the part number of the malfunctioning components were not available, and it is suspected that some of the reported problems represent failure of the engine-mounted fuel pump.

The overwhelming proportion of maintenance actions for the two pumps is to replace the unit. Failure modes are usually not determinable at the operating level. In an Army study of R&M problems of the military version of one of the more widely used civil helicopters, the fuel boost pump was reported to have leaking and burned failure modes. The majority of failure modes were undetermined, however.

Boeing Vertol experience has been that these boost pumps, which are predominantly direct-current, motor-driven units, have problems with the commutator brushes and tend to develop leaks between the pump and motor. The engine-mounted pumps are susceptible to contamination, and seizing is a common failure mode.

Problem Solution

Present Technology. — A further identification of the problem is needed. The failure modes must be determined in detail, and the relative performance of various design approaches should be established to determine if the problem exhibited reflects a unique design approach. A trade study should be made of the application of ac motor pumps for the fuel boost system. These motor pumps are brushless and operate completely submerged in fuel, thereby eliminating shaft seal problems.

Advanced Technology. — None proposed.

CIVIL HELICOPTER RELIABILITY PROBLEM F3

FUEL CELL LEAKAGE

Problem

Fuel cells are made of layers of fabric impregnated with an elastomer. The following causal factors have been experienced for leakage:

1. Mechanical damage during shipping, storage, installation, and maintenance results in punctures and tears.
2. Chafing on rivets, screw heads, sharp edges, and FOD such as loose hardware, tools, and other debris wears and punctures fabric. (Strips for chafing protection are installed at assembly but become dislodged or unbonded by fuel contamination.)
3. Delamination of fabrics, particularly at seams.
4. Stress concentration at fittings and attachments weakens fabric.
5. Shelf life: materials are age- and sunlight-sensitive.
6. Cell materials stiffen in the cold and may crack if handled at low temperature.

The problems vary with the details of construction.

Problem Solution

Present Technology. — Many of the problems are caused by methods of design execution, manufacturing processing, and the desire to minimize weight. Some examples of this are:

- Fuel cells are generally located in an inaccessible area. It is difficult to remove or install the tank without risking damage.
- Noncrashworthy tanks (believed to be the only type represented by this data) are made of thin fabric very susceptible to mechanical damage and chafing.
- The high rate of delamination of some manufacturers' fuel cells indicates the existence of a processing problem.
- Crashworthy fuel cells are becoming available for the civil helicopter market. These are much thicker and more tolerant of mechanical damage and chafing.

The problem of fuel cell leakage can be alleviated within present technology by design to cope with the maintenance and operational environment; specifically, design to give better access to fuel cell area and use of sturdier crash-resistant-type cells. These approaches, however, will adversely impact procurement cost and weight.

Advanced Technology. — Further research in materials and processing methods appears warranted to develop crashworthy, reliable fuel cells with a minimal adverse impact on cost and weight.

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